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Formaldehyde as an Indoor Air Quality Metric for Homes: Control Strategies and Energy Consequences

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Formaldehyde as an indoor air quality metric for homes: control strategies and energy consequences

by

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Dissertation

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Dedication

To my Beloved Wife of 35 years:

Lisa Marie Hunerwadel Jackson

The Love of my life, best friend,
stalwart companion
and supporter through thick and thin,
including: parenthood, grandparenthood
and four academic adventures.
May we have many more (non-academic) adventures in the coming decades.
The best is yet to come!

Our Children and Grandchildren:
Erik Jackson,
Larry Jackson, his wife Jenni Mares Jackson
Lily, Toby, Kyle, and TBD Jackson
May they be inspired by my example to work
to improve the environment in which they live
(however that unfolds in their lives),
to always persevere and embrace
the challenges and value of life-long learning

My Parents:
Dr. Horace D. Jackson and Mary Ann Cree Jackson
Who set an example of excellence in academic life,
family life, and how to love one's spouse for a lifetime,
and
Betty May Blom Ruth Jackson
(Discovered by my father in his 9th and her 8th decade - at the gym)
Who has enriched my life throughout my latest academic adventure

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“Persistence and Determination are Omnipotent”
Calvin Coolidge

A Benediction

May you be blessed as you seek to create a personal **constancy of purpose**:

> To Create harmony and balance between your personal and family life and professional vocation and avocations while **contributing the best of your abilities, love and enthusiasm**.

May you **improve continually and forever your production and service** (to family, friends, co-workers, customers, community, nation and world) by **minimizing variation** (to provide a stable environment in which to grow) and by **taking pride in your workmanship** (family, vocation and avocations).

Above all, may you find **Joy** in all you do.

Mark Cree Jackson (Inspired by the work of W. Edward Deming)
April 1995

Formaldehyde as an indoor air quality metric for homes:

control strategies and energy consequences

by

Mark Cree Jackson, PhD

The University of Texas at Austin, 2017

Supervisor: Richard L. Corsi

The renewed emphasis on energy conservation in the building sector has resulted in advances in residential building envelope design and construction that have led to ever tighter homes, lower energy consumption and reduced emissions of greenhouse gases. To keep pace with these advances, indoor air quality (IAQ) engineers are seeking ways to cost effectively achieve aldehyde, particularly formaldehyde (HCHO), and volatile organic compound (VOC) concentrations that meet government reference exposure limits (RELs). This work investigates four key concepts: (1) the efficacy of using HCHO as a surrogate for the impact of all aldehydes and VOCs on IAQ, (2) energy use/cost, compared with baseline energy used to achieve ASHRAE 62.2-2016 ventilation rates, required to attain desired RELs, (3) Disability Adjusted Life Year (DALY) benefits/value of reaching desired RELs and, (4) energy savings/value, identification and initial testing of a real-time HCHO monitor/controller to control variable speed ventilation and gas-phase filtration to achieve desired HCHO concentrations. This work is expected to inform decision makers and potentially be incorporated into several national standards and building programs such as ASHRAE 62.2, RESNET HERS® ratings, the U.S. EPA's EnergyPlus and U.S. DOE's Building America programs.

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Glossary

AMCV	Air Monitoring Comparison Values (TCEQ)
Ann. Avg.	Annual Average
AER(s)	Air Exchange Rate(s)
AL	Acceptable Limit
AM	Amarillo, TX
AR	Arcata, CA
ATSDR	Agency for Toxic Substances and Disease Registry
AU	Austin, TX
CA	Concentration Addition concept
CA OEHHA	California Office of Environmental Health Hazard Assessment
CAS#	Chemical Abstracts Service Number
$C_{CO2,\ in}$	Concentration of Carbon Dioxide indoors in ppb
$C_{CO2,\ out}$	Concentration of Carbon Dioxide outdoors in ppb
C_{HCHO}	Concentration of formaldehyde, always in ppb in this document
$C_{HCHO,\ in}$	Concentration of formaldehyde indoors
$C_{HCHO,\ out}$	Concentration of formaldehyde outdoors
C/DC	Constant / Demand Controlled (mAER)
CI	Confidence Interval
CO_2	Carbon Dioxide
CoC(s)	Contaminant(s) of Concern
Const.	Constant
CRA	Cumulative Risk Assessments
$C_{ref,\ i}$	Reference Concentration for Compound i
DALYs	Disability Adjusted Life Years
DB	Database
DC	Demand Controlled
DNPH	2,4-Dinitrophenylhydrazine
DOAS	Differential Optical Absorption Spectroscopy or Dedicated Outdoor Air System
D-R	Dose-Response
DSOA	Design Specification: Outdoor Air (used in EnergyPlus)
ER	Emission Rate
ESL	Effects Screening Level (TCEQ)

ESL_{LT}	TCEQ Long-term (annual) ESL
ESL_{ST}	TCEQ Short-term (1 hour) ESL
FA	Fairbanks, AK
GAC	Granular Activated Carbon
GPF	Gas Phase Filtration
GSHP	Ground Source Heat Pump
HCHO	Formaldehyde
HI	Hazard Index
HO	Houghton, MI
HPV	High Production Volume
IAQ	Indoor Air Quality
ID approach	Intake-DALY approach
IFRA	International Fragrance Association
IRPTC	International Register of Potentially Toxic Chemicals
KN	Knoxville, TN
LA	Los Angeles, CA
LOQL	Loss of Quality Life
$LOQL_{\$Ann}$	Monetized Annual Value of Loss of Quality Life
$LOQL_{\$LT}$	Monetized Lifetime Value of Loss of Quality Life
mAER	Mechancial Air Exchange Rate, h^{-1}
MeCN	Acetonitrile
Min	Minimum
MRL	Minimum Risk Level
MSEH	Multiple Sampling Event House
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NOAEL	No Adverse Effects Level
Non-Cap	Non-Capital Cost (i.e. of any equipment, including installation)
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OEHHA	Office of Environmental Health Hazard Assessment
PBPK	Physiologically Based Pharmacokinetic modeling
REL(s)	Reference Exposure Limit(s)
RPF	Relative Potency Factor
SCC	Societal Cost of Carbon
SE	Sampling Event
SFG	Surface Functional Groups
SID	Screening Information Database

Sp	Spiked Samples
SP or 1st Ext	Single Pass or 1st Pass Extraction Method
SRE	Sensible Recovery Efficiency
SSEH	Single Sampling Event House
SV	Shake-a-Vial Extraction Method
TCEQ	Texas Commission on Environmental Quality
TTD	Target Organ Toxicity Dose
U.S. DHHS	United States Department of Health and Human Services
U.S. DOE	United States Department of Energy
U.S. EPA	United State Environmental Protection Agency
UFFI	Urea Formaldehyde Foam Insulation
VOCs	Volatile Organic Compounds
w	With
WHO	World Health Organization

Chapter 1 Introduction

1.1 The Issue

As a result of the oil embargo of 1973-1974, there was significant motivation in the United States to reduce residential energy consumption. This resulted in programs to reduce infiltration of outdoor air into existing homes, as well as to reduce the amount of outdoor air required by national standard setting bodies in new homes. However, these actions had adverse consequences with respect to the quality of indoor air.

Wolfson (2012, 2013) provides a history of indoor air quality (IAQ) research, particularly in the early 1980s, including the elevated formaldehyde (HCHO) concentrations (C_{HCHO})[1] found in homes insulated with urea formaldehyde foam insulation (UFFI). Then as now, the emphasis was on the balance between energy use and IAQ. In the 1980s, C_{HCHO} in homes of over 200 ppb were common (Hawthorne et al. 1984). Today, energy conservation is now stimulated by climate change concerns. Residential buildings are being made tighter than ever, and 45many have very low air exchange rates (AERs).

[1] The word "formaldehyde" is abbreviated as HCHO. "Formaldehyde concentration(s)", always in ppb in this document, unless otherwise stated is abbreviated as C_{HCHO}. Where C_{HCHO} is reported in a reference in µg/m^3, it is converted to ppb by dividing by 1.23 and standard temperature (25 °C) and pressure (103.5 kPa) are assumed.

Formaldehyde is a known human carcinogen and sensory irritant (IARC, 2004;U.S. DHHS, 2014;CA OEHHA, 2013). Reference Exposure Limits (RELs) for HCHO have been reduced, and now range from 7-81 ppb. This reduction has resulted in the need to seek an "optimal balance" between energy use, IAQ and cost.

There are numerous aldehydes and volatile organic compounds (VOCs) found in homes with low air AERs. Concentrations of aldehydes (particularly HCHO) and volatile organic compounds (VOCs) above health-based RELs are found in tight homes that have been designed to minimize AERs in order to save energy (Offermann, 2010; Malkin-Weber, 2009; Dannemiller et al.; 2013 Hun & Jackson, 2014). However, achieving a specified REL for a single VOC or aldehyde does not guarantee that RELs will be achieved for other VOCs or aldehydes. Furthermore, whether the monetary value of lower C_{HCHO} based on a Disability Adjusted Life Years (DALYs) approach exceeds the additional incremental costs required to achieve C_{HCHO} beyond a minimum ASHRAE 62.2-2016 ventilation requirement baseline is unknown. To reduce health risks, creative solutions are needed to cost effectively achieve health-based RELs for aldehydes and VOCs in homes with minimal energy use. While the objective to balance energy and IAQ has been sought for over 40 years (Wolfson 2012), no published examples have been found to document the cost of achieving specific RELs of HCHO throughout the year.

Several other studies provide annual energy use and, in some cases, limited, short-term HCHO concentrations, but no monthly or average annual HCHO concentration other than those reported by Hun et al. (2013a&b) have been found. Singer and Willem (2012) show that to achieve a C_{HCHO} of 16 ppb [the National Institute for Occupational Safety and Health (NIOSH) REL], ventilation rates of 0.51 – 1.0 ACH are required. However, corresponding annual energy use required to achieve these ventilation rates was not provided.

Reducing energy consumption to achieve climate change goals and to simultaneously meet health-based IAQ criteria in residences are competing goals. This dissertation explores ventilation requirements, above the minimum required rates given in ASHRAE Std. 62.2-2016, needed to achieve desired C_{HCHO} with the least amount of additional energy.

1.2 Research Objectives

The three phases of this study are shown in Figure 1.1.

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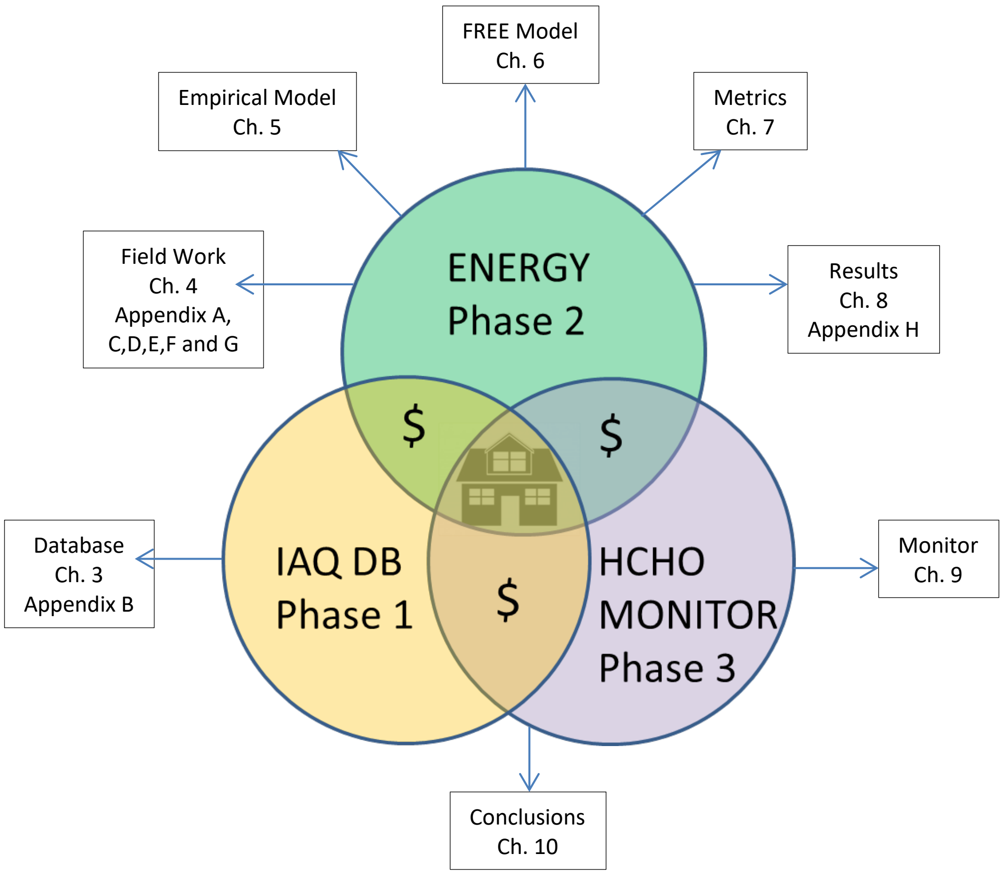


Figure 1.1: The three phases o f this study and their interactions

The efficacy of using HCHO as a surrogate for the impact of all aldehydes and VOCs on IAQ was explored during Phase 1 of this study through introduction and analysis of a new database (DB) of VOC and aldehyde test results from 249 homes. The feasibility and optimized annual energy use required to achieve various RELs for HCHO was analyzed as Phase 2 of this study using detailed energy modeling with EnergyPlus™ for two field trial homes. The energy savings/value of a real-time HCHO monitor to control variable speed ventilation was analyzed during Phase 3 of this study.

The ultimate goal of this dissertation is to develop a suite of metrics that combines energy use and a measure of IAQ that can inform decision makers and assure that strides being made in residential energy conservation are achieved while maintaining the same or better levels of IAQ. These metrics may eventually be used in modifying the Residential Energy Services Network, Inc. (RESNET) Home Energy Rating System (HERS®) used by the U.S. Environmental Protection Agency (U.S. EPA) for ENERGY STAR labeled homes, and the U.S. Department of Energy (U.S. DOE) in their Building America and National Builders Challenge programs (RESNET, 2006, 2012). An additional potential application of these metrics is to inform standard-making committees on future revisions to ASHRAE standard 62.2 (Ventilation for Acceptable Indoor Air Quality – for residences), ASHRAE Guideline 24 (Ventilation and Indoor Air Quality in Low-Rise Residential Buildings), the ASHRAE GreenGuide, and the forthcoming ASHRAE Indoor Air Quality Guide for residential buildings.

Specific objectives are:

1. Demonstrate if HCHO is a good surrogate for other aldehydes and VOCs based on a 249-home database of VOC and aldehyde measurements.

2. Characterize IAQ in four energy efficient site-built houses.
3. Perform ventilation and gas-phase treatment interventions in two of the houses in the field to develop a model that can be used as a tool for exploring the optimization of energy use and IAQ. The tightest house with the least variation from "traditional construction" and the house with the highest C_{HCHO} and most innovative envelope design – using a phase change material – were selected for the interventions.
4. Demonstrate which of the RELs for HCHO can be reasonably achieved.
5. Develop a generalizable suite of metrics that combine energy use and formaldehyde, as a measure of IAQ that can be applied by practitioners to optimize their designs to include both energy & IAQ.
6. Determine optimized energy use of the same two house designs used in the intervention study in one city in each of the eight Building America climate zones.
7. Determine the theoretical energy/dollar value of using a real-time formaldehyde monitor and additional cost of variable speed ventilation equipment versus continuous ventilation equipment to achieve desired RELs for HCHO year-round.
8. Coordinate and analyze initial calibration test results of a potential real-time HCHO monitor/controller to determine realistic minimum detection limits and applicability to control ventilation to achieve HCHO RELs of interest.

1.3 Scope of Research

The following describes the specific scope of this dissertation:

1. A previously developed 61-home database of aldehydes and VOCs (Jackson et al., 2011a) was expanded to a 249-home database using existing sampling reports provided by Matrix Analytical Labs. The objective of developing this expanded database was to explore whether HCHO is a good surrogate for other aldehydes and VOCs in a larger database.
2. This study involved baseline measurements of aldehyde and VOC concentrations, and air exchange rates (AERs) in four unoccupied demonstration houses built in Oak Ridge, Tennessee. Thus, the impact of furnishings is specifically excluded. The experimental work was limited primarily to HCHO. Other indoor pollutants were specifically excluded from the scope of this project. As reported by Logue et al. (2012), it is acknowledged that the health impact (as measured by DALYs) of particulates, specifically PM2.5 is approximately an order of magnitude greater than the DALY impact of formaldehye. Real-time particulate monitoring and control [with high efficiency filtration (MERV 13+) and point source exhaust (kitchen exhaust) may have a much gerater impact on health than control of C_{HCHO} by source reduction, increased ventilation or GPF discussed in this dissertation. Particulates are not considered in this study. While there is significant (orders of magnitude) variation in the DALY

health risks of contaminants of concern (CoC), based on the work presented by (Jennifer M Logue et al., 2012), the central tendancy of the DALY risk for formaldehyde is within the top 5 CoC [PM2.5, Second Hand Smoke, Radon (for smokers) with a tie for formaldehyde and acrolein].

3. This study involved field interventions using ventilation and gas-phase filtration conducted in two of the four test houses.
4. All supply ventilation air was filtered through a HEPA/carbon filter to minimize the impact of outdoor concentrations of formaldehyde. The energy used for filtering air through a HEPA/Carbon filter (either ventilation air or for gas-phase filtration) was included in the overall energy for each scenario, including the energy recovery ventilator (ERV) and gas phase filtration (GPF) scenarios. The additional energy used by the fan in the ERV was assumed to be small when compared with the energy used for filtering all the ventilation air through the HEPA/Carbon filter and was not included in the overall energy used for the ERV scenarios only. A model analysis was made to determine the amount of energy as a percent of total energy fan energy for filtration through the HEPA/Carbon filter was in one of the target homes described in 2 above in each of the eight climate zones for both constant mechanical ventilation and demand controlled ventitation at an indoor temperature of 24.4 ^oC. The validity of the assumption that fan energy in ERV-A was negligible was verified for the case where $C_{HCHO} \leq 16$ ppb in Austin. The percent of energy used by the GPF fan in a single

scenario in Austin for the case where C_{HCHO} ≤ 16 ppb reported in this dissertation. Energy used by the HEPA/Carbon filter or ERV is compared to the fan efficacy required in the 2015 International Energy Conservation Code (IECC) (IECC, 2015).

5. Regression analysis of experimental data in MATLAB® and Excel® was used to obtain a correlation between environmental conditions, system operation parameters, and indoor C_{HCHO} as reported by Hun et al. (2013a). This correlation is the key output from the field work, and permits calculation of emission rates throughout the year based on environmental conditions and building operating parameters. The emission rates are the bridge between the field work and computer modeling.
6. Computer modeling using EnergyPlus™ (a U.S.DOE energy simulation software program that calculates energy use for heating and cooling loads using a heat balance sub-hourly iterative approach) and customized pre- and post- processors developed for this project in Excel® was used. An author-developed FREE (Formaldeyde Reduction and Energy Efficiency) computer modeling was used to estimate the impact of implementing source reduction, and various ventilation / gas-phase filtration strategies to predict and optimize energy use. The FREE model proviced energy used by these strategeis required to achieve the various RELs for HCHO in both of the test homes where field interventions were made.

7. The scope of modeling was limited to 10 minute increments in the EnergyPlus™ model and one hour increnents in the FREE model for which mechanical ventilation rates are changed based on indoor temperature changes (typically a winter and summer thermostat setting) and changes in natural ventilation due to outdoor environmental conditions (i.e., temperature and wind speed).
8 For DALY calculations, population average residential occupancy characteristics used by Logue et al. (2012) with a cancer age-dependent adjustment factor (ADAF) of 1.6, 70% occupancy, and a per person inhalation rate of 14.4 m^3/day were assumed.
9. Changes in mechanical ventilation to address load shifting for utility savings are specifically excluded from the scope.
10. In the modeling phase of this project, it is assumed that a cost-effective HCHO sensor and control system that can turn ON/OFF fans, etc., at any desired concentration (i.e., down to 5 ppb) will be available in the future. The state-of-the-art of such HCHO sensors was reviewed. Initial testing of a prototype HCHO monitor/controller was performed by an outside lab with a custom built thermally jacketed test chamber designed and procured by the author.
11. ASHRAE 62.2-2016 ventilation rates are used to determine baseline indoor $C_{HCHO,in}$ and energy use. Required energy use to achieve desired $C_{HCHO,in}$,within defined humidity parameters, is determined with a constant

outdoor concentration of formaldehyde ranging from 1 to 5 ppb based on the specific site. Similarly, for one scenario, required energy use to achieve desired $C_{CO2,in}$ is determined with a constant outdoor concentration of carbon dioxide, $C_{CO2,out}$ = 400 ppm at all sites. Constant CO_2 generation from four human occupants who (for the CO_2 modeling) are assumed to be in the home continuously is used. The same continuous occupancy was assumed for all scenarios for calculating DALYs. The ORNL test homes included thermal heaters to simulate occupancy. Emissions of VOCs from occupants were not considered in this stuidy. Changes in outdoor $C_{CO2, out}$ and indoor CO_2 generation rates during working and sleeping periods are specifically excluded from the scope of research. A sensitivity analysis of the impact of a range (5, 10 and 15 ppb) of outdoor concentrations of formaldehyde ($C_{HCHO, out}$) was conducted for one location (Los Angeles).

Chapter 2 Background

2.1 Formaldehyde

Formaldehyde (HCHO) is the lowest molecular weight aldehyde. A summary of chemical and physical properties of HCHO is provided in Table 2.1.

Table 2.1: Chemical and Physical Parameters of Formaldehyde

Parameter	Value
CAS Registry No[1]	50-00-0
Molecular formula[1]	HCHO
Melting Point[1]	-92 ^oC
Molecular Weight[1]	30.03 g/mol
Boiling Point[1]	-21 ^oC
Dipole Moment[1]	2.33 D
Solubility[1&2]	Soluble in water, ethanol, ether, acetone 0.45 g HCHO/g H_2O at 28±2 ^oC
Henry's law constant[1]	2.5 x 10^3 M atm^{-1} (25 ^oC)
$Log(K_{ow})$[1]	-0.83
Dynamic diameter[3]	2.43 Å

[1]Salthammer et al. (2010) and references provided therein
[2]Grűtzner & Hasse (2004)
[3]Pei & Zhang, (2011) and references provided therein

Formaldehyde occurs in a gaseous form inside occupied, conditioned residential homes, and only occurs in liquid form outdoors on very cold winter days. The high solubility of HCHO in water is of particular interest, as formaldehyde can be "washed" from the air to some degree when it passes through a wet air conditioning evaporator coil in the summer. Another potential impact of the solubility of HCHO is transfer of HCHO from the outgoing to incoming air streams of an Energy

Recover Ventilator (ERV) – specifically those using rotary enthalpy wheels as described by Hult, et al. (2014). The ERVs in the ORNL test houses were disabled for this study in order to avoid this issue, as discussed further for the fixed membrane ERVs modeled in Appendix H.

2.2 Health Effects of Formaldehyde

Health effects of formaldehyde are classified into cancer effects (discussed in section 2.3.1) and non-cancer effects (discussed in section 2.3.2). Monetization of health risk using disability adjusted life years (DALYs) and value of a DALY are discussed in section 2.3.3. The range of recommended concentrations of HCHO in residences is more than an order of magnitude (7 – 81 ppb). Key RELs are listed in section 2.4.

2.2.1 Cancer Effects of Formaldehyde

"Formaldehyde [is] the greatest contributor to the cumulative cancer risk from exposure to contaminants that are typically found indoors."

(Hun et al., 2010)

Formaldehyde concentrations in residences have become a greater concern over the last decade as formaldehyde is increasingly recognized by cognizant bodies as being a carcinogen. Formaldehyde has been recognized by several government agencies as a known human carcinogen (IARC, 2004, 2012; U.S. DHHS, 2011; CA OEHHA, 2015a) and several government agencies have reduced the concentrations of exposure they recommend for both carcinogenic and non-carcinogenic endpoints (FEMA, 2008a; Health Canada, 2006; Mandin, et al. 2009; CA OEHHA, 2012; U.S. EPA(DRAFT), 2010; WHO, 2010). Nielsen and Wolkoff (2010) summarized effects of HCHO and argued that, based on epidemiological findings, the WHO concentration of 81 ppb is “preventive of carcinogenic effects”. Health effects, both carcinogenic and non-carcinogenic, are briefly reviewed in Section 2.3 of this study.

2.2.1.1 Classification of Formaldehyde as to Carcinogenicity

Several international, federal and state agencies have modified their classification of HCHO from a probable to a known human carcinogen. The International Agency for Research on Cancer classified formaldehyde as “carcinogenic to humans” on 15 June 2004 (IARC, 2004). In June 2011, the U.S. Department of Health & Human Services (U.S. DHHS) in their National Toxicology Program’s 12th Report on Carcinogens, and reconfirmed in the 13th Report on Carcinogens, reclassified formaldehyde from “reasonably anticipated to be a human carcinogen”, as defined for 30 years since 1981, to “known to be a human carcinogen”. Specific cancers cited were: sinonasal, nasopharyngeal and lymphohematopoietic (specifically myeloid leukemia) cancers (U.S. DHHS, 2011, 2014).

The California Office of Environmental Health Hazard Assessment (CA OEHHA) has listed formaldehyde as a “chemical known to the State of California to cause cancer or reproductive toxicity” since 1988 (CA OEHHA, 2013a). In contrast to the U.S. DHHS, the U.S. EPA currently classifies formaldehyde as a class B1 carcinogen, a “probable human carcinogen” (U.S. EPA, 2012a).

2.2.1.2 Carcinogenic Risk from Inhalation Exposure to Formaldehyde

The level of cancer risk and associated concentration of formaldehyde according to the current and proposed U.S. EPA and current CA OEHHA risk estimates are listed in Table 2.

Table 2.2: Estimate of Carcinogenic Risk from Inhalation Exposure to HCHO

	Concentration of Exposure		
	U.S. EPA		CA OEHHA[3]
Risk Level	Current[1]	Proposed[2]	
E-4 (1 in 10,000)	6.5 ppb (8 μg/m^3)	0.7 ppb (0.9 μg/m^3)	0.7 ppb (0.9 μg/m^3)
E-5 (1 in 100,000)	0.65 ppb (0.8 μg/m^3)	0.07 ppb (0.09 μg/m^3)	0.07 ppb (0.09 μg/m^3)
E-6 (1 in 1,000,000)	0.065 ppb (0.08 μg/m^3)	0.007 ppb (0.009 μg/m^3)	0.007 ppb (0.009 μg/m^3)

[1] U.S. EPA (2012a)
[2] U.S. EPA(DRAFT) (2010) based only on risk from nasopharyngeal cancer, Hodgkin’s lymphoma and leukemia
[3] CA OEHHA (2009) – converted from a unit risk factor to concentration

Note that it is essentially infeasible to achieve E-5 and E-6 risk levels, and only in exceptional cases can the EPA’s current 1 in 10,000 risk level [6.5 ppb (8 µg/m3)] be achieved in residences. With concentrations of HCHO as described in section 2.5 of this study ranging from ~2 to greater than 170 ppb (3 to >200 μg/m^3), risk levels in those homes could range from 1 in 10,000 to 1 in 100 incidence of cancer from formaldehyde exposure over a 78 year lifetime[2], depending on which carcinogenic risk level is most accurate. These values are based on an assumed linear dose-response model without a lower threshold or upper plateau.

An external review process was undertaken by the U.S. Department of Health and Human Services (U.S. DHHS), Centers for Disease Control and Prevention (CDC), & the National Institute for Occupational Safety and Health (NIOSH) (2013) to modify NIOSH policy for determining RELs for carcinogens in the workplace. The goal is "to keep exposures below the 95% lower confidence limit estimate of the dose expected to produce 1 in 1,000 excess risk of cancer as a result of a 45-year working lifetime exposure", which is "at least an order of magnitude higher than the cancer risk permitted in the United States for the general public". In addition, "NIOSH RELs will be health-based and the institute will no longer specifically consider technical achievability (i.e., ability to control exposures) in establishing RELs" (U.S. DHHS, CDC, & NIOSH, 2013). If adopted, this revised NIOSH policy may lead to additional pressure to reduce HCHO concentrations in both workplaces and residences.

[2] A 78 year lifetime is assumed throughout this study as recommended by the U.S. EPA (2011)

2.2.2 Non-Cancer Effects of Formaldehyde

The non-cancer adverse effects of HCHO are primarily head and upper-respiratory irritation, particularly in the eyes and respiratory tract. Additional effects include: allergic sensitization, cough, sneezing, shortness of breath and reduced lung function. Children, particularly those with asthma, are at higher risk than adults following exposure to formaldehyde (CA OEHHA, 2008).

Rumchev et al. (2002) reported that based on a study of 88 young children with asthma and 104 controls, $C_{HCHO} \geq 49$ ppb increases the risk of asthma in children. Dannemiller et al. (2013) completed a study of 70 homes of asthmatics in Boston, MA, and found suggestive evidence ($p < 0.078$) that exposure to elevated C_{HCHO} is related to poorly controlled asthma. In the Dannemiller study, children with very poorly controlled asthma lived in homes with a 57% higher geometric mean C_{HCHO} (54.0 ppb vs. 34.4 ppb) than other asthmatic children. In contrast, Wolkoff and Nielsen (2010) reviewed the non-cancer effects of formaldehyde, primarily chronic sensory irritation of the eyes and airways, and concluded that there is no epidemiological association between formaldehyde concentrations and exacerbation of asthma.

2.2.3 Disability Adjusted Life Years and Monetization of Health Risk

Disability Adjusted Life Years (DALYs), with units of years lost annually per 100,000 persons, is a metric to quantify the health risk of various practices or exposures. Annual average exposures to HCHO are required to calculate the DALY risk from HCHO for any given year.

Logue et al. (2012) used median lognormal cancer mass intake-based DALY factors, an annual indoor C_{HCHO} of 56 ppb (the assumed population concentration based on 77 residential air pollutant studies analyzed by Logue et al.(2011)), and population averages for inhalation rates and age dependent adjustment factors for cancer exposure (ADAF). They predicted that approximately 46 DALYs are lost per year per 100,000 population, or 8.2 DALYS/10 ppb/100,000 persons/year. When a DALY is valued at $150,000 (2014 U.S. Dollars), as used as a base case by Aldred et al. (2015), and four individuals are assumed to reside in the home, an estimate of the annual health benefit of a 10 ppb reduction in C_{HCHO} is ~$50/year. Extending this analysis to an indoor C_{HCHO} >100 ppb, the value of reducing C_{HCHO} by 100 ppb could be ~$500/year or more in the year immediately following construction. Assuming a simple economic payback of 10 years, in this "worst-case" scenario, a justifiable combination of the initial incremental capital cost of control technologies as well as annual energy use and maintenance for ten years could be ~$5,000 or more. As shown in Chapter 3, these values will be much higher if either the 68% or 95% upper confidence interval (CI) of the lognormal median are used for the cancer mass intake-based DALY factor.

Based on the cost of the gas phase filtration systems reported by Hun et al. (2013a), the value of decreasing C_{HCHO} cannot be justified solely on DALY reductions. However, if ventilation and particulate or gas-phase filtration equipment is installed to reduce other contaminants, such as ozone and PM2.5, then only the incremental equipment, maintenance and energy costs of controlling HCHO would need to be economically justified.

This simplistic screening analysis points to the value of control strategies that have a low incremental cost, and that could be easily added to existing heating, ventilating, and air conditioning (HVAC) equipment. For example, metal-oxide catalysts for removal of HCHO are currently in the development stage (Fisk et al. 2011; Han et al. 2012; Sidheswaran et al. 2011). Activated carbon filters with a low pressure drop that can be regenerated nightly are also under development (Sidheswaran et al. 2012).

The actual monetized benefit of decreasing the C_{HCHO} depends on a variety of factors. These include the value placed on a DALY for people of different ages, number of years considered (e.g., 10 years or a lifetime), number and age of people in the home, e.g., cancer risk to an infant (<2 years) is 10x that of an adult, C_{HCHO} over the life of the building, economic assumptions, etc.

2.3 Reference Exposure Limits (RELs)

Reference Exposure Limits for HCHO, shown in Table 2.3, are concentrations below which significant adverse health effects are not expected. Each agency specifies different populations, exposure averaging times, and safety factors, which accounts for the large range of limits.

Table 2.3: Reference Exposure Limits (RELs) for HCHO

Agency	Concentration	Time Period
CA OEHHA[1]	7 ppb [9 μg/m^3]	8-hr and chronic
	44 ppb [55 μg/m^3]	1-hour acute
France AFSSET[2]	8 ppb [10 μg/m^3]	
EPA (Proposed)[3]	2.8-11 ppb [3.4 – 13.5 μg/m^3]	Chronic (annual)
EPA (Current)	None	
FEMA/NIOSH/CDC[4]	16 ppb [20 μg/m^3]	10-hr
CA ARB[5]	26 ppb [32 μg/m^3]	8-hr
Health Canada[6]	40 ppb [50 μg/m^3]	8-hr
	100 ppb [123 μg/m^3]	1-hr acute
NEPM[7]	40 ppb [50 μg/m^3]	24-hr
WHO[8]	81 ppb [100 μg/m^3]	30 min and chronic

[1] California Office of Environmental Health Hazard Assessment (CA OEHHA, 2012)
[2] French Agency for Environmental and Occupational Health Safety, AFSSET (Mandin et al. 2009)
[3] U.S. Environmental Protection Agency (U.S. EPA(DRAFT), 2010)
Note: the EPA is currently re-assessing formaldehyde and is currently at the Interagency Science Consultation stage of their review with a Projected End Date TBD (U.S. EPA, 2015b).
[4] Federal Emergency Management Agency (FEMA, 2008a, 2008b)
[5] California EPA Air Resources Board (CA EPA Air Resources Board, 2004).
[6] (Health Canada, 2006)
[7] Australian National Environment Protection (Air Toxics) Measure (National Environmental Protection Council Service Corporation, 2011)
- Monitoring Investigation Level (MIL)
[8] World Health Organization (WHO, 2010b)

The range of REL's spans an order of magnitude, with the WHO concentration being the highest for non-industrial exposures. A review paper on cancer effects of HCHO by Nielsen and Wolkoff (2010) supports the WHO REL.

Subsequent to the high formaldehyde concentrations found in "Katrina trailers" in 2007, the U.S. Federal Emergency Management Agency (FEMA) implemented procurement guidelines that require mobile and park model trailer manufacturers to provide trailers with measured C_{HCHO} <16 ppb [the current National Institute for Occupational Safety and Health (NIOSH) formaldehyde 10-hr formaldehyde limit] (FEMA, 2008a, 2008b).

For their own buildings, the U.S. EPA used 16 ppb as the threshold (maximum) allowable indoor air concentration standard in their Environmental Specifications – Section 01445 (U.S. EPA, 2006). The latest reference to using this specification was found in the General Service Administration (GSA) report regarding construction of the EPA Region 8 Headquarters building (U.S. GSA, 2013). The GSA report shows that after occupancy the indoor C_{HCHO} was 16-21 ppb, compared to an outdoor concentration of 4 ppb.

The California Office of Environmental Health Hazard Assessment (CA OEHHA, 2008, 2012) has set an 8-hr and chronic exposure level for formaldehyde based on non-cancer effects of 7 ppb (9 µg/m^3). This relatively stringent concentration can be exceeded in the outdoor air of some cities (Salthammer, 2013).

The U.S. EPA has been developing a chronic Reference Concentration for inhalation (RfC) of formaldehyde. In an approximately 1,000 page draft external review report, the EPA indicated an expected chronic Reference Concentration (RfC) for formaldehyde exposure by inhalation to be in a range between 2.8 and

11 ppb (U.S. EPA(DRAFT), 2010). This document was reviewed by the National Academy of Sciences (NAS) for the EPA resulting in a 194 page report that found "recurring methodologic problems" and recommended numerous changes to the methodology and other revisions prior to release of the EPA report (NAS, 2011). Development of the inhalation RfC remains to be completed (U.S. EPA, 2015b). Once the EPA posts their final assessment of an inhalation RfC (which may be very different than that proposed in their draft report of 2010), it is anticipated that this value will dictate what C_{HCHO} will be acceptable in the built environment in the U.S.

While regulatory guidance on C_{HCHO} continues to be in flux, information on the ability, costs, and benefits of achieving the various RELs should be valuable to decision makers.

2.4 Sources of Formaldehyde in Residential Buildings

Formaldehyde is a ubiquitous indoor air contaminant that has been studied extensively for over 40 years. The primary source of HCHO in buildings is pressed wood products (PWP). Additional sources include combustion devices, certain personal care products (e.g., cosmetics), ozone reactions with some terpenes (Wolkoff & Nielsen, 2010), durable (permanent) press clothing, and wood floor finishes (U.S. CPSC, 2013). Salthammer et al. (2010) provide an excellent review on the state-of-knowledge related to HCHO and its sources in buildings.

2.5 Formaldehyde Concentrations in Residential Buildings

Several researchers have investigated C_{HCHO} in residential buildings. Key studies as well as those related to this study are shown in Table 2.4. The majority of these studies show average C_{HCHO} below the Health Canada 40 ppb REL, but few below the NIOSH/FEMA/CDC 16 ppb or CA OEHHA 7 ppb REL. Jackson et al. (2011b) reported that levels below the CA OEHHA levels were achievable, but only after significant remediation of a 47 year old home with exceptional source control combined with gas-phase filtration and ventilation. Hun et al. (2010) analyzed data from the Relationships of Indoor, Outdoor, and Personal Air (RIOPA) study and reported a median C_{HCHO} of 17 ppb across 179 homes, most of which were greater than 5 years of age. Offermann (2009) measured HCHO in 105 new homes in California and found a median C_{HCHO} of 29 ppb.

Table 2.4: Residential Indoor Formaldehyde Concentrations

Location	Number of Homes	Year(s)	Range C_{HCHO}, ppb	Mean ppb	Median ppb	Comment	Reference
Tennessee	40 homes	1982-3	<25 - 634	78	NA	Variation: Daily 2X; Seasonal > 10X	Hawthorne et al. (1984)
U.K.	174	1991-3	<1 - 166	20	NA	Bdrms 1504 Smpls	Berry et al. (1996)
Australia	192	1998-9	<10 - 182	24	NA	Living rooms	Rumchev et al. (2002)
U.S.	179	1999-2001	10 (5th %) – 25 (95th %)	17	17	Homes > 5 years old	Hun et al. (2010)
Mexico City	4	2001	14 - 74	35[1]	30[1]	10-h avg	Baez et al. (2006)
Canada	96	2005	8 - 73	24[2]	NA	Winter – 24h Avg	Gilbert et al. (2008)
California	105	2007-8	4 - 110	NA	29	New homes-24-h vg	Offermann (2009)
Massachusetts	70	2008-10	5 - 132	35	36		Dannemiller et al. (2013)
Texas	2	2011	2 - 11	NA	NA	After remediation	Jackson et al. (2011)
orldwide	3370 samples	2011	NA	56	NA	13 studies, 3370 samples	Logue et al. (2011)
Tennessee	4	2011-13	22 - 172	NA	NA		Hun et al. (2013a)
Australia	40	2015	4 - 27	15	15	86% 5 - > 50 yrs old	Cheng et al. (2015)
California	24 Bed rm 24 Kitch	2015	10 – 38 7 – 27	18 18	14 16		Less et al. (2015)

[1] Mean and Median calculated from data in reference
[2] Calculated from geometric means of C_{HCHO} reported in each air change rate quintile

2.6 Formaldehyde Concentrations in Outdoor Air

Formaldehyde concentrations measured in outdoor air ($C_{HCHO, out}$) are shown in Table 2.5. Most studies indicate average outdoor concentrations <5 ppb. However, in large metropolitan areas, specifically where biofuels are used for transportation fuel, outdoor concentrations can be considerably higher.

Table 2.5: Outdoor Air Formaldehyde Concentrations, $C_{HCHO, out}$

Location	**Number of Samples**	**Year(s)**	**Range $C_{HCHO, out}$ ppb**	**Mean, ppb**	**Reference**
Worldwide	24 papers	1961-2007	<1 to 150	NA	Salthammer (2013)
Mexico City	12	2001	4-16	9	Baez et al. (2006)
U.S.	179	1999-2001	2 (5^{th} %) - 8 (95^{th} %)	5	Hun et al. (2010)
Tennessee	4	2011	2 to 4	3	Hun et al. (2013)
U.K.	126	1991-3	0 - 9	2	Berry et al. (1996)
Australia	237	2012	16 ppb max	7.9 ± 2.7	NEPC (2013)
Australia	95	2012	2.1 ppb max	2.1 ± 0.8	NEPC (2013)
California	24	2011-3	0 - 11	4	Less et al. (2015)

Salthammer (2013) provides a review of both indoor and outdoor C_{HCHO}. While the average $C_{HCHO, out}$ was 40 ppb in Los Angeles in 1961, a maximum $C_{HCHO, out}$ of 150 ppb was reported. It should be noted that these measurements were taken before catalytic converters were used in automobiles. Salthammer also reports on a more recent 2003 study in Riverside, CA, where maximum outdoor concentrations of 11 ppb were reported. Elevated concentrations of 113 ppb found in Rio de Janeiro in 2001 are attributed to increased use of biofuels. With the use of improved combustion engines, these values declined to average concentrations of ~40 ppb by 2009. Salthammer (2013) suggests that "typical" average $C_{HCHO, out}$ in central Europe and the U.S. range from 5-15 ppb. He further suggests that in cities with high concentrations of photochemical smog (such as Beijing), average $C_{HCHO,out}$ range from 20-30 ppb with peaks of 40-50 ppb.

National Environmental Protection Council (2013) reports outdoor $C_{HCHO, out}$ measured at two sites in Australia from 1/1/2012 to 12/31/12 using Differential Optical Absorption Spectroscopy (DOAS). In South-East Queensland, 247 valid results were reported with an annual average concentration of 7.9 ppb with a standard deviation of 2.7 ppb and a maximum 24-hour average concentration of 16.0 ppb. In Gladstone, 95 valid results were reported with an annual average concentration of 2.1 ppb with a standard deviation of 0.8 ppb and a maximum 24-hour average concentration of 4.0 ppb.

Salthammer (2013) considers an indoor $C_{HCHO, in}$ of 40 ppb and $C_{HCHO,out}$ of 15 ppb in urban areas as "normal", but not necessarily "safe" or "acceptable". Indoor concentrations between 40 and 80 ppb are considered "elevated" and indoor concentrations greater than 80 ppb are considered "polluted" (based on the WHO criteria). $C_{HCHO,out}$ above 15 ppb are considered "elevated".

2.7 Measurement of Formaldehyde in Air

The established method of measuring formaldehyde is the EPA TO-11a method (U.S. EPA, 1999). This method uses sampling pumps to collect air samples in the field by pulling 200-500 mL/min of air through tubes containing 2,4-dinitrophenylhydrazine (DNPH) for 1 to 24 hours. Formaldehyde and other low molecular weight aldehydes react with DNPH to form unique derivatives that are subsequently extracted in the lab using acetonitrile (MeCN) and separated for identification and quantification using high pressure liquid chromatography (HPLC), typically with UV detection.

A low-cost, real-time, formaldehyde monitor that has a detection limit below the NIOSH (16 ppb) or CA OEHHA (7 ppb) REL is not currently available. Progress has been made in this area and a ventilation controller was developed to monitor C_{HCHO} below 80 ppb (DC Group International, 2013). A further enhancement of the DC Group International monitor by the author is described in Chapter 9.

A HCHO monitor based on a chemical sensor element in which HCHO reacts with β-diketone and ammonia, and subsequent spectrophotometric analysis to measure the extent of that reaction, is reported to provide continuous 30 minute readings of C_{HCHO} down to <20 ppb (Maruo et al. 2008a, 2008b, 2009, 2010, Maruo & Nakamura, 2011). A commercially available HCHO monitor (Shinyei Technology

Co., Ltd., 2011) using this technology and utilized in the present study is described in more detail in Section 4.3 under Subtask 3.4.

Additional techniques for continuous monitoring of formaldehyde are available. Sidheswaran et al. (2013) report on measurement of HCHO using an Ionicon Proton Transfer Reaction – Mass Spectrometer (PTR-MS) and Interscan 4160-500B monitors. A continuous formaldehyde monitor based on tunable infrared laser differential absorption spectroscopy (TILDAS) technology is commercially available (Aerodyne Research Inc., 2013). This equipment is currently used for atmospheric trace gas detection with a limit of detection of 0.15 ppb with a 100 s averaging time as reported by Jimenez et al. (2005) and in traffic-related pollution studies as reported by Shields et al. (2013). Poppendiek (2016) confirmed that the Aerodyne equipment was used in the study reported by Poppendiek et al. (2016), which is the first known IAQ study that monitored real-time concentrations of HCHO with a sensitivity of 0.1 ppb at a one second sampling rate. A purportedly "low cost" colorimetric method with a detection limit of 4 ppt with a 100 cm optical path and a time resolution of 15 minutes is described by Sassine et al. (2013). A monitor that uses a pre-concentrator and subsequent thermal desorption with an electrochemical sensor that can detect HCHO at ppb levels was reported by Xiao et al. (2011). An E-nose technology developed by the National Research Council Canada (NRCC) reportedly provides ppb level monitoring of HCHO using conjugated polymers (NRCC 2011, Deore et al. 2011). A SnO_2/NiO composite film produced using pulsed laser deposition is reported to measure formaldehyde with a minimum detection limit of ~10 ppb in dry air; cross-sensitivity with water vapor, CO_2, alcohols, etc. may invalidate this approach for field applications (Dunford et al. 2010).

2.8 Strategies for Reducing Human Exposure to Formaldehyde

2.8.1 Source Reduction

Source reduction should be the first step to reduce HCHO in residences. In most cases, using alternative materials that do not emit HCHO is far less expensive than increasing ventilation rates to dilute HCHO after the fact.

The State of California (CA EPA Air Resources Board, 2007) and the U.S. Government (U.S. Congress, 2010) have recently enacted legislation to limit HCHO emissions from many pressed wood products (PWP). The federal legislation entitled "The Formaldehyde Standards for Composite Wood Products Act" limits the emission rate of formaldehyde from certain products. The final rule to implement this legislation was issued by the U.S. EPA on July 27, 2016 and was published in the Federal Register on December 12, 2016 with an effective date of February 10, 2017 (U.S. EPA, 2016).

Full implementation of these regulations, using a ventilation rate of 0.25 air changes per hour (ACH), are expected to reduce HCHO concentrations in new homes to ~73 ppb (vs. 140 ppb using 2002 industry average emission rates) (Hun et al. 2010). This ~50% reduction in C_{HCHO} is encouraging, but is somewhat masked by the fact that the initial concentration was so high (140 ppb). Even with the use of the new, lower HCHO emission rqtes, C_{HCHO} is near the upper limit of international government recommendations, 4.5 times the concentration required by FEMA for emergency trailers and 10x the concentration recommended by the State of California. Without further control mechanisms, using similar materials and building tighter than 0.25 ACH to reduce energy use, concentrations will easily exceed the range of recommended concentrations (Malkin-Weber et al. 2009). Further reductions in emission rates, increased ventilation rates, gas phase filtration or other control methods will be required to achieve C_{HCHO} recommended by NIOSH/FEMA/CDC (16 ppb) or CA OEHHA (7 ppb). Scenarios to evaluate these methods are outlined in Ch. 6 and modeling results presented in Ch. 8.

Careful evaluation and selection of every material used in building a residence as well as every item brought into the residence can reduce emission rates of HCHO. Careful selection of non-PWP building materials, such as MgO sheathing and drywall replacement, concrete block or other non-HCHO containing building materials can reduce the amount of formaldehyde embedded in the frame and shell of the building. These non-PWP materials can be used to replace HCHO containing PWP materials, such as oriented strand board (OSB) and composite wood structural members. Avoidance of manufactured wood flooring with formaldehyde containing adhesives or coatings in preference to hard surface ceramic or terrazzo flooring can also reduce emissions of formaldehyde. The Healthy Building Network's Pharos Project provides a comprehensive database of over 1,600 building products with profiles of more than 35,000 chemicals that designers and architects can use to select materials without specific contaminants of concern (Healthy Building Network, 2014).

Selection of furnishings without composite wood materials, as well as careful selection of all cleaning, personal care and hobby products, pesticides and other items brought into the home can reduce the burden of both formaldehyde and other contaminants of concern (CoC).

Formaldehyde is a by-product of combustion, in addition to other indoor environmental hazards including ultrafine particles (UFP), PM2.5, CO, NO_2, etc. (Traynor et al., 1982; Francisco et al. 2010; Logue et al., 2014). Avoidance of gas appliances, particularly open combustion including gas stoves, fireplaces, non-vented combustion appliances, and any atmospheric vented combustion sources including furnaces and hot water heaters can reduce sources of formaldehyde in homes. Refraining from burning candles is an occupant action that can also eliminate a source of formaldehyde (Derundi et al., 2014).

2.8.2 Ventilation

Ventilation and source control are the primary approaches that have been used to achieve desired C_{HCHO}. Historically, ASHRAE set required ventilation rates for residences (ASHRAE, 2016) based on odor and not on health guidelines. Recent ASHRASE guidance (ASHRAE, 2016) has lower ventilation rates than those historically based on odor. A full history of the ASHRAE ventilation rates is provide by Sherman(2015)

An air exchange rate of 0.5 hr^{-1} is recommended to keep formaldehyde levels at or below 50 ppb in new homes based on typical formaldehyde emission rates (Sherman & Hodgson, 2004). The need for relatively high ventilation rates is supported by several other researchers (Gilbert et al. 2008, Offermann, 2009; Singer & Willem, 2012).

Additional guidance on designing for enhanced environments is available from the American Institute of Architects. The Guidelines for Design and Construction of Hospitals and Outpatient Facilities provides detailed design guidance. ASHRAE Standard 170-2013 for Ventilation of Health Care Facilities can assist architects and engineers in creating levels of air quality equivalent to those required in a hospital patient room, e.g., 2 ACH of outside air with minimum efficiency rating value (MERV) 14 particulate air filters (AIA, 2014).

Turner et al. (2013) provide a net present value (NPV) method to optimize ventilation rates and IAQ using a DALY approach considering formaldehyde and acrolein. They base their model on low/medium/high emission rates for formaldehyde of 9.7/30.3/88.2 μg/(h m^2) and acrolein of 1.3/1.9/6.1 μg/(h m^2). These will be compared to the emission rates found in the field trial houses in Chapter 8. The medium sized (195 m^2 / 2100 ft^2 floor area with 2.74 m / 9 ft ceilings), 3 bedroom house considered by Turner et al. (2013) is based on the CEC Title 24 housing prototypes presented by Nittler and Wilcox (2006). The ASHRAE 62.2-2016 minimum required ventilation rate for such a home is 43 L/s (93 cfm) which is equivalent to 0.30 ACH for this house. Turner et al. (2013) report that, based on DALYs from formaldehyde and acrolein, and energy costs, optimal outdoor air ventilation rates for their 195 m^2 house with low/medium/high emission rates are 20/48/74 L/s (43/102/158 cfm) which are 45%/107%/163% respectively of the ASHRAE 62.2-2016 (ASHRAE, 2016) minimum required ventilation rate. The optimal outdoor air ventilation rates of 20/48/74 L/s (43/102/158 cfm) are equivalent to air exchange rates (AER) of 0.14/0.32/0.50 h^{-1}.

Turner et al. (2013) present the mass balance equation shown in equation 2.1 for a well-mixed indoor space.

$$dC_{HCHO,\ in}/_{dt} = E/_{V} - \mathrm{AER} * \mathrm{C}_{\mathrm{HCHO,\ in}} - \mathrm{kC}_{\mathrm{HCHO,\ in}} + \mathrm{p} * \mathrm{AER} * \mathrm{C}_{\mathrm{HCHO,\ out}} \qquad (2.1)$$

where,

$C_{HCHO,\ in}$ = indoor concentration of HCHO [μg/m^3]

$C_{HCHO,\ out}$ = indoor concentration of HCHO [μg/m^3]

E = emission rate of HCHO [μg/h]

V = house volume [m^3]

AER = air exchange rate [h^{-1}]

k = first order loss/decay rate constant for HCHO [h^{-1}]

p = penetration coefficient [--], a value between 0 and 1.

For formaldehyde, Turner et al. (2013) assume a first order loss rate of 0, a penetration factor of 1, and an outdoor air concentration of 2.4 ppb. Assuming steady state conditions, Eq. 2.1 reduces to:

$$C_{HCHO,\ in} = {}^{E}/_{(AER * V)} + C_{HCHO,\ out} \quad (2.2)$$

Using Turner et al. (2013) Low/Med/High emission rates (ER) for their medium size home, $C_{HCHO,\ in}$ using the ASHRAE 62.2-2013 ventilation rate, which includes infiltration, and Turner et al. (2013) optimal AER as calculated above are shown in Table 2.6.

Table 2.6: Steady-State C_{HCHO} with ASHRAE Ventilation Rates & Turner ERs

Turner et al. Emission rate category	Emission Rate [µg/(h m^2)]	Steady-State $C_{HCHO, in}$, ppb	
		ASHRAE 62.2-2016 Ventilation	Turner et al. Optimal Ventilation
Low ER (5th %ile)	9.7	12	24
Med ER (Median)	30.3	32	31
High ER (95th %ile)	88.2	90	56

Table 2.6 shows that at the High ER, C_{HCHO} is greater than the WHO REL of 81 ppb for the 2016 ASHRAE 62.2 ventilation rates. Only with the 2016 ASHRAE 62.2 ventilation rates in the low (5th percentile) ER category is C_{HCHO} below the FEMA/NIOSH/CDC REL of 16 ppb. The optimal ventilation rates determined by Turner et al. (2013) result in C_{HCHO} ranging from 24-56 ppb. Based on this analysis using the criteria presented by Turner et al. (2013), higher ventilation rates than ASHRAE 62.2-2016 minimum ventilation rates are justified for the medium and high formaldehyde emissions rates presented by Turner et al., (2013).

Extensive work has been done to optimize ventilation control systems to achieve equivalent exposure to occupants as those encountered in buildings ventilated continuously in accordance with ASHRAE recommended levels (Sherman, Mortensen, & Walker, 2011; Sherman, 2006; Singer & Willem, 2012). These are generally applicable to approaches that seek to meet health based C_{HCHO} requirements rather than a prescribed ventilation rate.

Sherman and Walker (2011) provide a dynamic control method (Residential Integrated Ventilation Energy Controller, RIVEC) to achieve an equivalent relative exposure and dose over a 24-hour period as continuous ventilation at ASHRAE 62.2-2007 rates. Their dynamic controller shuts off whole-house ventilation for four hours during peak utility periods and when supplemental ventilation from kitchen and bathroom exhaust provide ventilation. This approach is shown to provide contaminant exposure that is better than or equivalent to continuous ventilation at ASHRAE levels. However, this approach is based solely on the prescribed ASHRAE ventilation rate and does not focus on an actual health-based exposure level (i.e., REL).

Singer and Willem (2012) summarize information showing a reduction of C_{HCHO} with increased ventilation. Reductions were observed in all individual homes tested (n = 9), despite an increase in emission rate with higher AER. Importantly, Singer and Willem (2012) show that AERs of 0.51-1.0 ACH are needed to approach the NIOSH (16 ppb) formaldehyde REL. Additional ventilation, source reduction or alternate methods to reduce C_{HCHO} are required to approach the CA OEHHA (7 ppb) 8-hr and chronic REL.

Heat and energy recovery ventilators (HRVs & ERVs) can help reduce energy consumption, if not the capital, cost of achieving high AERs. There are two primary concerns with the performance of these ventilators: energy efficiency, both sensible and latent, and cross-over of contaminants from the exhaust stream to the supply stream. Chen et al. (2012) describe a high efficiency combination HRV, ERV and Economizer (HERV) and control system that maximizes the sensible and latent efficiency based on the indoor and outdoor temperature and humidity. With this optimized HERV system, the annual combined sensible and latent efficiency range from 38 – 62% depending on the climate zone. This compares to 47-67% latent efficiency and 70-80% sensible effcieincy of the fixed membrane ERV-A and 35-89% latent efficiency and 67-98% sensible efficiency for the fixed membrane ERV-B evaluated in Appendix H. The efficiency depends on air flowrate, indoor and outdoor temperature. Sensible Recovery Efficiencies (SRE) at 0 ^{o}C reported by Home Ventilating Institute (2017) range from 54-91%.

The issue of cross-over of contaminants in ERVs is a potential concern of ERV membranes and latent heat recovery wheels as described by Hult, et al. (2014). For latent heat recovery wheels, the desiccant used can affect the cross-over rate for HCHO from 6 – 35% as reported by Kodama (2010). In a study of seven different ERV membranes for fixed ERVs, Huizing et al. (2013) reported that cross-over rates for HCHO range from 0.3 - 9.6%.

To effectively achieve the lower RELs of 7 or 16 ppb for HCHO, it is anticipated that multiple approaches will be required, including: source reduction, elevated ventilation rates, and gas phase filtration (GPF). In areas of the country where $C_{HCHO,\ out}$ are relatively high, lower RELs may not be feasible without GPF of all incoming outdoor air, rigorous source control, reduced indoor temperature, and significant amounts of GPF on of recirculated air. The energy and cost of achieving these low C_{HCHO} where outdoor concentrations are elevated may not be economically viable. This study intends to show, in terms of both energy and cost, what it will take to achieve defined C_{HCHO} RELs (i.e. WHO 81 ppb, NIOSH 16 ppb or CA OEHHA 7.3 ppb) and humidity (>20% RH; ≤ 48% RH when Tout > 0 ^{o}C, ≤ 26% RH when Tout ≤ 0 ^{o}C) levels in homes in any of the eight Building America climate zones at an assumed $C_{HCHO,\ out}$ of 2-5 ppb depending on location. A sensitivity analysis of elevated $C_{HCHO,\ out}$ is conducted in one location. A full list of the 296 scenarious modeled is described in Ch. 6.

This study incorporates field interventions using positive and negative ventilation and gas-phase filtration individually, to study $C_{HCHO,\ in}$ in two test houses. In addition, modeled source reduction, dehumidification, gas-phase filtration and dynamically-controlled ventilation is used to optimize energy use in achieving defined target C_{HCHO} RELs in specific homes, i.e., rather than a predefined ventilation flowrate.

2.8.3 Gas-Phase Filtration (GPF)

Gas phase filtration (GPF) has been implemented using off-the-shelf carbon-based (with a proprietary additive) equipment in combination with ventilation and source reduction, to dramatically reduce C_{HCHO} in a house that was recently remodeled, as well as a house where the objective was to achieve the lowest possible C_{HCHO} (Jackson, et al. 2011b). This same off-the-shelf carbon-based filtration equipment was used in this project to explore the efficacy of GPF (Hun et al. 2013a&b).

Carter (2013) and Carter et al. (2011) describe work on two commercially available bituminous carbon based granular activated carbons (GACs), one that is nitrogen modified and one that is not, and show that HCHO absorption capacity is related to the density of basic surface functional groups (SFGs) and even more robustly related to electron-donating potential. Increased HCHO adsorption was associated with increased nitrogen content. Carter (2013) also reported a novel nitrogen-doped GAC with enhanced HCHO absorption capacity. This novel nitrogen-doped GAC was produced in small (20-30 g) test quantities using a mixture of argon and ammonia gas at 950 ^{o}C. When exposed to a stream of HCHO at a concentration of 36 ppb in nitrogen, at 95% breakthrough, the novel nitrogen-doped GAC held 162 μg HCHO/g GAC, 8.5 times greater than the 19 μg HCHO/g

GAC formaldehyde holding capacity of a commercial non-modified GAC tested the same way. Carter (2013) and others cited therein suggest that nitrogen-containing GACs exhibit catalytic activity. Catalytic activity of GACs would increase the apparent adsorption capacity of these materials.

Novel, low-cost, low-energy, gas-phase filtration based on MnOx, currently in the laboratory stage of development, shows promise for high efficiency (80%) removal of HCHO in combination with a central HVAC filter that can be replaced quarterly (Sidheswaran, et al. 2011a). A detailed study of eight chemisorbents and catalysts was conducted by Han et al. (2012), with the best material showing a 15-30% single pass removal efficiency of formaldehyde when the catalyst was incorporated into a particulate filter.

Zhang et al. (2011) reviewed numerous photocatalytic, thermal catalytic and ozone-catalytic oxidation air cleaning technologies and found well-designed sorption systems to be effective at removing HCHO. These may produce pollutants from the interaction of ozone with contaminants sorbed to the media, and long-term performance of such air cleaners is not well understood. Ewlad-Ahmed et al. (2012) demonstrated functionalized meso-silica material and a novel green nanosilica material with active amine sites for removal of HCHO.

Wang (2014) measured the efficiency of HCHO removal using sheep's wool as a chemisorbant using a portable air cleaner packed with 10 pounds of wool. While the economics of using wool as a chemisorbant for HCHO may be challenging and frequent filter changes required in a residential application, this work does show the promise of using natural substances for removal of HCHO. Of particular interest is that amino acids found in wool are very reactive with HCHO, particularly aspartic acid (87%) and glutamic acid (72%) as reported by Caldwell and Milligan (1972), the most reactive of the amino acids Wang reviewed. Corfield & Robson (1955) report that aspartic acid comprises 6.8% and glutamic acid 14.5% of wool by mass. This may provide another avenue of enhancing the removal of HCHO if these amino acids can be applied to some other absorbent, such as activated carbon, that can result in higher densities of aspartic and glutamic acid than the 0.37 and 0.80 g/L respectively that would be found in wool in the 5.5 g/L packing density of wool used in the air cleaner experiment reported by Wang. Ghosh & Collie (2014) and references provided therein describe the use of wool in several configurations of 'electret' filters without providing specific filtration efficiencies for HCHO.

2.8.4 Passive Removal Materials (PRMs)

Passive Removal Materials (PRMs) such as drywall, either by itself (Matthews et al. 1987) or with additives such as chitosan (Wang et al. 2011) or MnO_x (Sekine, 2002; Sekine & Nishimura, 2001), have been explored as possible low-energy and low-cost approaches to reduce C_{HCHO}. Wang (2014) suggests that wool may be used as a passive removal material in the form of carpets, curtains and other furnishings.

Reducing ozone concentrations indoors will reduce the production of formaldehyde stemming from ozone reactions with terpenes. Cros et al. (2012) studied several materials as passive materials for the removal of ozone in indoor environments. Activated carbon mats that could be hung from walls and perlite ceiling tiles were found to be effective in decreasing ozone concentrations indoors. If these materials used functionalized carbon with amines, they may provide passive removal of HCHO as well – at least immediately following construction when C_{HCHO} is highest.

Nomura and Jones (2015) describe the use of aminosilica incorporated into latex paint as a potential passive removal material. In this process, three commercial silicas were functionalized with 3-aminopropyltrimethoxysilane (APS) and mixed with latex films. The concept is of interest as painted surfaces typically cover the majority of walls and ceilings in residences. As with all chemisorbants, it’s efficacy will be exhausted once all active sites are filled. While the active life of the formaldehyde adsorbing aminosilica needs to be evaluated further, it may be useful in reducing HCHO concentrations in newly renovated homes.

By injecting HCHO into a test room to achieve C_{HCHO} of 2.9 to 7.9 times higher than initial background concentrations in the space, Plaisance et al. (2013) determined a decay rate constant (k) for HCHO of $0.37 \pm 0.07\ h^{-1}$ and a deposition velocity (Dep) of $(2.53 \pm 0.51) \times 10^{-3}\ cm\ s^{-1}$. This decay rate is consistent with the $0.40 \pm 0.24\ h^{-1}$ reported by Traynor et al. (1982) based on a chamber study of HCHO decay after generation from a gas stove. Plaisance et al. (2013) explore various indoor sinks for formaldehyde and suggested that, based on HCHO's affinity for water, surface films may be possible removal paths. This suggests that wet cooling coils may be a removal mechanism. Additional removal paths suggested by Plaisance include: absorption to water sorbed onto airborne particles, photolysis of formaldehyde at wavelengths <380 nm, and oxidation of formaldehyde by ozone, hydroxyl or nitrate radicals.

2.9 Summary

This chapter provides background information on formaldehyde, including physical properties, cancer and non-cancer health effects. Reference exposure limits from several agencies were provided as well as measurement and control methods for formaldehyde and representative C_{HCHO} in residences and outdoors.

This background information will be used in Chapter 3 to analyze a new database developed in this study of aldehydes and VOCs measured in 249 residences. The objective is to determine the efficacy of using C_{HCHO} as a metric for IAQ, and as a surrogate for other aldehydes and VOCs.

The techniques for reducing exposure to formaldehyde discussed in Sections 2.8.1-2.8.3 will be used in Chapter 8 in modeling the cost ($ and energy) required to achieve desired RELs for HCHO in two energy efficient homes studied by the author at Oak Ridge National Laboratories (ORNL).

Chapter 3 Formaldehyde as an IAQ Indicator

3.1 Conceptual Development

The efficacy of using formaldehyde (HCHO) as an IAQ indicator and as a general surrogate for all aldehydes and VOCs that are contaminants of concern (CoC) is explored in this chapter. A new database of VOCs, including aldehydes, measured in 249 single-family detached homes is introduced. This database is analyzed to identify CoC based on toxicity, how well the identified CoC correlate with HCHO using Spearman correlation coefficients, frequency of occurrence, contribution to an overall hazard index (HI) calculated for the entire database, disability adjusted life years (DALYs). Finally, Spearman correlation coefficients are calculated between HCHO and the identified CoCs.

Sherman and Hodgson (2004) proposed that HCHO be used as a basis for minimum residential ventilation standards rather than human bioeffluents, which has been the indirect basis for setting minimum ventilation rates. Formaldehyde was proposed as it is commonly present in houses, readily quantifiable, and approaches or exceeds concentrations of concern for sensory irritation and cancer effects (ibid.). Sherman and Hodgson proposed a 'minimum ventilation rate' that would keep the concentration of formaldehyde (C_{HCHO}) less than 100 ppb (with 99% confidence) as well as a 'guideline ventilation rate' that would keep C_{HCHO} <

50 ppb (with 90% confidence). Based on data collected from 14 houses, at a 99% confidence level the floor-area normalized mean whole house emission factor was 83 μg/ h m^2. This emission rate is comparable to the "high emission rate" of 88 μg/ h m^2 described by Turner et al. (2013) based on C_{HCHO} measurements in 105 new homes by Offermann (2009). Sherman and Hodgson's emission rate required a "minimum ventilation rate" of 0.28 h^{-1} to keep C_{HCHO} < 100 ppb. Similarly, at a 90% confidence level, the whole house emission factor was 65 μg/h m^2. This emission rate required a "guideline ventilation rate" of 0.43 h^{-1} to keep C_{HCHO} < 50 ppb. For simplicity and to be conservative, a guideline ventilation rate of 0.50 h^{-1} was recommended by Sherman and Hodgson to keep C_{HCHO} < 50 ppb. While this approach is an improvement over ASHRAE 62.2-2016 (ASHRAE, 2016) required ventilation rates that are non-health based, it generalizes the emission rate of all houses based on the average emission rates from a set of only 14 houses and does not optimize/control ventilation rates based on real-time C_{HCHO} in a specific house under varying environmental conditions.

For some indoor environments, formaldehyde may not be the best metric for IAQ. For example, Zaatari et al. (2016) showed that DALYs attributed to PM2.5 and acrolein were an order of magnitude higher than DALYs attributable to formaldehyde for retail stores. However, retail stores generally have much higher outdoor air exchange rates and therefore are more challenged by pollutants of outdoor origin such as PM2.5

3.2 Data Analysis Methods

3.2.1 Database Development

This chapter deals with a significant expansion of the initial database reported on by Jackson et al. (2011a). The objective of developing an expanded database is to determine if HCHO is a good surrogate for the impact of all VOCs including aldehydes on IAQ.

Matrix Analytical Labs of Farmers Branch, TX provided the author 340 datasets from sequential residential air sample reports, based on sampling completed from July 2008 through October 2014, without any identifying information other than U.S. Geographical Regions/Divisions and date (month/year). Residential air samples were analyzed for clients who had an IAQ complaint, a physician ordered air sample, or to verify a reduction in contaminants after remediation. This database may not be representative of the entire population as only individuals in socio-economic groups that could afford several hundred dollars for air sampling are included in this study. This may be similar to the population represented by new homes built in California and studied by Offermann (2009), but may be significantly different than the housing population in the RIOPA study that surveyed older homes where occupants did not pay for the air sampling Hun et al. (2009).

Only datasets that included matched adsorbent tubes (for VOCs) and DNPH tubes (for light aldehydes) data, from samples that were collected for 24 +/- 2 hours, were included in the database. Samples were collected using pumps that were calibrated with a NIST traceable volumetric displacement calibration meter at Matrix Labs before and after field sampling was performed. EPA test method TO-17 was used for VOCs (accuracy +/- 25%) and a modified EPA test method TO-11a was used for aldehydes (accuracy +/- 15%). Matrix uses an extraction method which combines 5 ml of acetonitrile (MeCN) with the DNPH from the sampling tubes in a small vial that is shaken with a mechanical shaker for 30 minutes. This modification provides a more complete extraction of the DNPH-aldehyde derivatives than the single pass extraction method specified by EPA test method TO-11a. Ozone scrubbers were not used upstream of DNPH tubes in most cases.

A sampling event (SE) is defined as the average of all samples taken in a house within a 48-hour time period. Houses in which there is only one SE are defined as a single sampling event house (SSEH). Houses in which there is more than one SE are defined as multiple sampling events houses (MSEH). Sampling events from MSEH are considered independent sampling events as they were taken at different times after some form of remediation to the indoor environment was implemented. The distribution of formaldehyde concentrations found in this database was compared with those found in other North American databases.

3.2.2 Identification of Contaminants of Concern

The Texas Commission on Environmental Quality (TCEQ) has developed a list of 6,299 constituents in air with corresponding Effects Screening Levels (ESLs) (TCEQ, 2015). ESLs "are used to evaluate potential for effects to occur as a result of exposure to concentrations of constituents in the air. ESLs are based on data concerning health effects, odor/nuisance potential, and effects on vegetation. They are not ambient air standards. If predicted or measured airborne levels of a constituent do not exceed the screening level, adverse health or welfare would not be expected to result." (TCEQ, 2014). Short-term ESLs are for 1-hour averages while long-term ESLs are for annual averages.

In this study, a contaminant of concern (CoC_i) is defined as any compound which occurs in >5% of the SEs and for which the concentration from the 24 ± 2 hour indoor air samples in the database (DB) exceeds a reference concentration for compound i (C_{ref_i}) in >5% of the SEs. For this study, a reference concentration

(C_{ref_i}) was assigned for each compound i as the lower of the short-term (1 hour) or long-term (annual average) Effects Screening Level (ESL) assigned by the Texas Commission on Environmental Quality. If the California Office of Environmental Health Hazard Assessment (CA OEHHA) chronic reference exposure limit (cREL) is less than the TCEQ ESL, the CA OEHHA cREL is used as $C_{ref,i}$. This occurs for formaldehyde, toluene, benzene, and naphthalene. Four different reference concentrations for formaldehyde (81 ppb, 40 ppb, 16 ppb, and 7 ppb based on WHO/Health Canada/NIOSH/California OEHHA reference concentrations respectively as shown in Table 2.3) were explored. For this study, it is assumed that the concentrations measured in 24 ± 2 hour samples are equivalent to annual average concentration. It is acknowledged that this definition of a CoC represents a very conservative metric for exposure to these constituents, but one where "adverse health effects, odor/nuisance potential or effects on vegetation would not be expected to result" (TCEQ, 2014).

There are several additional criteria that may be of concern for any given compound. These include whether the compound is one that contributes to asthma (an asthmagen), neurotoxicity, cancer, reproductive risk, or allergic sensitivity (e.g. fragrances). Compounds found in >5% of the SEs were reviewed to assess whether they are listed on any of the criteria lists shown in Table 3.1. While lists for other criteria exist, the lists chosen represent a broad range of potential health hazards.

Table 3.1: Criteria Lists Reviewed for compounds found in >5% of SEs

Criteria List	**Reference**
TCEQ ESL	TCEQ (2015)
Asthmagens – per NIH 2011 list	Mlade et al. (2011)
Neurotoxicants – list of 214 compounds	Grandjean and Landrigan (2014)
Developmental Neurotoxicants	Grandjean and Landrigan (2014)
Fragrance – 3059 compounds	IFRA (2011)
ATSDR – chronic value	ATSDR (2015)
CA OEHHA REL – REL_C	CA OEHHA (2014a)
CA OEHHA Prop 65 list – 6/19/15 or Notice of intent to list	CA OEHHA (2015), (CA OEHHA, 2015b)
Prop 65 - Cancer	
Prop 65 -Developmental	
CA OEHHA NSRL / MADL	CA OEHHA (2013b)
GRO (Gas Range Organics) (Alkanes C6-C10)	U.S. EPA (2003b)
Carcinogenic human-health combined damage and effect factor $\left[{\partial DALYS_{Cancer}}/{\partial intake}\right]$	Huijbregts et al. (2005)
Noncarcinogenic inhalatory human-health combined damage and effect factor $\left[{\partial DALYS_{non-Cancer,inh}}/{\partial intake}\right]$	

3.2.3 Formaldehyde Concentration vs. Number of Contaminants of Concern

The C_{HCHO} vs. # of CoC as defined in Section 3.3.1 (a very conservative approach), is another comparison used to test the theory that C_{HCHO} is a reasonable metric for IAQ in homes. The correlation between formaldehyde concentration and the number of CoC is a significant metric of interest in this dissertation.

3.2.4 Hazard Index (HI)

In a smaller version of the Matrix database (n=75), Jackson et al. (2011a) reported on a dimensionless hazard index (HI) described by van Gestel et al. (2011) that assumes toxicity risks of individual contaminants of concern are additive in mixtures of CoC. The HI is used or recommended, often as a screening method, by the ACGIH, EPA, NAS, NRC, OSHA and ATSDR (ATSDR, 2004 and references therein) "to assess non-cancer health effects of a mixture". This approach uses the concept of concentration addition (CA) where, as described by van Gestel et al. (2011), it is assumed that "each chemical in the mixture contributes to toxicity, even at concentrations below its no-effect concentrations". The concept of independent action (IA) uses a summation of the probability of an effect from each separate compound and is only applied to compounds above their no observable adverse effects level (NOAEL) that have different modes of action (van Gestel et al., 2011).

The CA concept is typically used when a mixture of chemicals has the same mode of action as when the target organ, system, or health effect are the same and "is not applicable to complex mixtures with many components" (ACGIH, 2010). The CA method produces more conservative results than the IA method and provides "accurate predictions of combinations effects, even with mixtures composed of chemicals that operate by diverse modes of action" (van Gestel et al., 2011). Mixtures of compounds can exhibit antagonistic effects where a mixture is not as toxic as the individual components as well as synergistic effects where mixtures are more toxic than the individual components in addition to potentiation and masking effects (van Gestel et al., 2011, Mumtaz, 2010, and references therein).

The US EPA's Superfund Program uses the CA concept to calculate a HI as an initial screening without regard to impacts on specific organs or organ system (Mumtaz, 2010 and references therein). In this screening method, a HI > 1 is cause for additional concern or analysis. Note that the magnitude of the HI is highly dependent on the acceptable limit (AL) or reference concentration ($C_{ref,\ i}$) selected for each compound. Frequently, an inhalation reference concentration target organ toxicity dose (TTD) or minimum risk level (MRL) is used as the $C_{ref,\ i}$. More refined HI approaches calculate HI based on specific organs or organ systems affected by chemicals, target organ toxicity values, or relative potency factors (RPFs) which require dose-response (D-R) data for all compounds in the mixture. For more detailed analysis, the EPA recommends a chemical interaction HI based on binary interactions data (for which there is limited data) when compounds are known to interact non-additively. Comprehensive cumulative risk assessments (CRA) for mixtures of chemicals are evolving based on physiologically based pharmacokinetic (PBPK) modeling, but require extensive information on each compound (Mumtaz, 2010, WHO, 2010a, Pohl, et al., 2003).

The concept of concentration addition (CA) is used to calculate a HI in this dissertation as a conservative estimate, for screening purposes, of the impact of the toxicity of mixtures of compounds. Reference concentrations (C_{ref_i}) are taken as the lower of the TCEQ short-term or long-term ESL with the exception of HCHO, toluene, benzene and naphthalene as described above in Section 3.2.2. Only the compounds that occur in >5% of the SEs and have a $C_{ref, i}$ are included in the HI.

For each individual SE_j, the hazard HI is given by Eqn. 3.1.

$$HI_{SE_j} = \sum_{i=1}^{n} C_i / C_{ref_i} \tag{3.1}$$

where,

HI_{SE_j} = hazard index of SE_j [- -]

j = sampling event index

C_i = the concentration of the i^{th} CoC in the SE

$C_{ref, i}$ = the reference concentration of the i^{th} CoC in the SE i = contaminant of concern index

n = number of compounds in SE_j that occur in >5% of all SEs

The distribution of HI_{SE_j} across the entire database provides an indication of whether the distribution is normal or lognormal.

The total HI of the entire database (DB) is the sum of the HI of all SE's as shown in Eqn. 3.2.

$$HI_{DB} = \sum_{j=1}^{m} HI_{SE_j} \tag{3.2}$$

where,

HI_{DB} = hazard index of the total database [- -]

j = sampling event index

m = number of SEs in the database [- -]

HI_{SE_j} = hazard index of SE_j [- -]

The percent of HI_{DB} in each SE is the HI in each individual SE divided by the HI in the entire DB as shown in Eqn. 3.3.

$$HI_{SE_j}(\%) = {HI_{SE_j}}/{HI_{DB}} \tag{3.3}$$

where,

$HI_{SE_j}(\%)$ = hazard index of SE_j as a % of the HI of the total DB

j = sampling event index

HI_{SE_j} = hazard index of SE_j [- -]

HI_{DB} = hazard index of the total database [- -]

The cumulative % of HI_{DB} vs. HI_{SE_j} provides a second visual perspective of the distribution of the HI across the entire DB.

Similarly, the HI due to each CoC_i across the entire DB can be calculated as shown in Eqn. 3.4

$$HI_{CoC_i} = \frac{1}{C_{ref,i}} \sum_{j=1}^{m} C_{i,j} \tag{3.4}$$

where,

HI_{COCi} = hazard index of CoC_i from the entire database

i = contaminant of concern index

j = sampling event index

m = number of SEs in the database

The percent of HI_{DB} due to CoC_i is calculated as shown in Eqn. 3.5

$$HI_{CoC_i}(\%) = {}^{HI_{CoC_i}}\!\big/_{HI_{DB}} \qquad (3.5)$$

where,

$HI_{CoCi}(\%)$ = hazard index of CoC_i as a % of the HI of the total DB

HI_{CoCi} = hazard index of CoC_i [- -]

i = Contaminant of Concern index

HI_{DB} = hazard index of the total database [- -]

The HI_{CoCi} of all CoC_i that contribute at least 5% of the HI_{DB} provides a metric to identify the most important CoC as a subset of the CoC defined in section 3.2.2.

3.2.5 Disability Adjusted Life Years

Disability Adjusted Life Years (DALYs) is a metric used to quantify the human health impact of contaminants of concern (CoC). Logue et al.(2011 and 2012a) provided an analysis of the impact of CoC in U.S. residences. Using an intake-DALY (ID) approach, Logue et al. (2011 and 2012a) calculated the DALY impact of assumed population average concentrations of individual VOCs, including select aldehydes, using cancer and non-cancer intake fractions calculated by Huijbregts et al. (2005) based on non-human animal toxicity studies. Aldred et al. (2015) calculated DALYs for formaldehyde and acetaldehyde individually using the

ID approach described above and modeled concentrations of formaldehyde and acetaldehyde.

This study expanded the work of Logue et al. (2011 and 2012a) and Aldred et al. (2015) to include contaminants of concern (CoC) found in the Matrix database that have DALY damage factors as per Huijbregts et al. (2005). Only the inhalation values found in Huijbregts et al. (2005) for carcinogenic and non-carcinogenic human-health damage are considered. Non-carcinogenic, oral human-health damage is not considered in this study, even though a small fraction of contaminants from the air may be introduced, absorbed in saliva and swallowed through the oral route. Air-to-dermal uptake was also not considered.

DALYs for each compound were calculated using the Intake-DALY method described by Logue (2012) using equations 3.6 and 3.7.

$$DALYs_i = \left[\frac{\partial \mathrm{DALYs}}{\partial intake}\right]_i (\mathrm{intake}_i) \tag{3.6}$$

$$DALYs_i = (C_i)(V_B)(POP)(freq)(CF)\left[\left[\left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_i (ADAF)\right] + \left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_i\right] \tag{3.7}$$

where,

DALYs$_i$ = Disability Adjusted Life Years lost per year per 100,000 people due to exposure to contaminant of concern i

[DALYs lost/year/100,000 people]

Intake = annual pollutant intake of gaseous contaminant of concern i per person [$kg \cdot person^{-1} \cdot year^{-1}$]

C_i = average concentration of contaminant of concern i during exposure events [$\mu g \cdot m^{-3}$]

V_B = average volume of air breathed per person per year [$m^3 \cdot person^{-1} \cdot yr^{-1}$]

POP = exposure population, 100,000 people for this study [people]

freq = exposure frequency, or fraction of one year when exposure occurs [--]

CF = conversion factor = 1 x 10^{-9} [kg/μg]

$\left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_i$ = cancer intake combined damage and effect factor for gaseous pollutant i [$year \cdot kg^{-1}$]

ADAF = age dependent adjustment factor for cancer exposure [--]

$\left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_i$ = non-cancer intake combined damage and effect factor for gaseous pollutant i [$year \cdot kg^{-1}$]

$DALYs_i$ are calculated for each of the multiple compounds for each SE at the compound i's individual concentration in each SE.

The cancer and non-cancer combined damage and effects factor from Huijbregts et al. (2005), $\left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,g}$ and $\left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,g}$, as well as the uncertainty factors $k_{\partial D/\partial I,\ carcinogenic,g}$ and $k_{\partial D/\partial I,\ non\text{-}carcinogenic,g}$ are lognormal distributions that Huijbregts et al. (2005) obtained using parametric bootstrap methods. In this work, a subscript "$_g$" has been added when the distribution is a lognormal distribution and a subscript "$_n$" has been added when the distribution is a normal distribution. Care must be taken when calculating DALYs as the cancer and non-cancer components of the DALYs should only be summed when they are normally distributed.

The lognormal uncertainty factor, k_g, known as the dispersion factor by Slob (1994), is defined in Eqn. (3.8, here M_g is the median (50% percentile) and X is any stochastic variable that is lognormally distributed.

$$Prob\left\{\frac{M_g}{k_g} < X_g < k_g M_g\right\} = 0.95 \qquad (3.8)$$

Note that M_g/k_g is the 2.5th percentile and k_gM_g is the 97.5th percentile of the lognormal distribution. The uncertainty factor, k_g, is defined as shown in Eqn. 3.9 :

$$k_g = \left(\frac{97.5^{th} - 2.5^{th} percentile}{M_g}\right) \qquad (3.9)$$

The uncertainty factor of the DALYs due to cancer, $k_{\partial D/\partial I,cancer,g}$, and the uncertainty factor of the DALYs due to non-cancer health impacts, $k_{\partial D/\partial I,non\text{-}cancer,g}$, are defined as shown in Eqns. (3.10 and 3.11:

$$k_{\frac{\partial DALYs,cancer,i,g}{\partial intake}} = \left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,97.5\%ile,g} \Big/ \left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,median,g} \tag{3.10}$$

$$k_{\frac{\partial DALYs,non-cancer,i,g}{\partial intake}} = \left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,97.5\%ile,g} \Big/ \left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,median,g} \tag{3.11}$$

Huijbregts et al. (2005) defines k_i = (97.5th %ile / 2.5th%ile) with uncertainty assumed to be lognormal.

The lognormal standard deviations of $\sigma_{i,g}$ are obtained by taking the square root of the lognormal uncertainly factors, as 2σ ~ 95% of the lognormal distribution, or the span from 2.5%ile – 97.5%ile, thus Eqns. (3.10 and 3.11 can be rewritten as Eqns. 3.12 and 3.13.

$$\sigma_{\frac{\partial DALYS,cancer\ i,g}{\partial intake}} = \sqrt{k_{\frac{\partial DALYS,cancer,i,g}{\partial intake}}} \tag{3.12}$$

$$\sigma_{\frac{\partial DALYs,non-cancer,i,g}{\partial intake}} = \sqrt{k_{\frac{\partial DALYS,non-cancer,i,g}{\partial intake}}} \tag{3.13}$$

The cancer and non-cancer intake combined damage and effect factors in lognormal distributions given by Huijbregts et al. (2005) and lognormal standard deviations (Eqns. (3.12) and (3.13)) must be converted to normal distributions by taking their natural logs (Ln) prior to being used in Eqn. 3.7 as shown in Eqns. 3.14 to 3.17:

$$\left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,n} = ln\left\{\left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,g}\right\} \tag{3.14}$$

$$\left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,n} = ln\left\{\left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,g}\right\} \tag{3.15}$$

$$\sigma_{\frac{\partial DALYs,cancer,i,n}{\partial intake}} = ln\left(\sigma_{\frac{\partial DALYs,cancer,i,g}{\partial intake}}\right) \tag{3.16}$$

$$\sigma_{\frac{\partial DALYs,non-cancer,i,n}{\partial intake}} = ln\left(\sigma_{\frac{\partial DALYs,cancer,i,g}{\partial intake}}\right) \tag{3.17}$$

This work, as did the work by Corsi et al. (2014), which calculated DALYs due to ozone, uses a transparent, analytical method to calculate the uncertainty of summing the cancer and non-cancer combined damage and effects terms described by Spandaro & Rabl (2008). In addition, the lognormal central value (median) of the DALYs and lognormal standard deviation for the two CoC determined by Corsi et al. (2014) were expanded to 22 CoCs in this dissertation. This work extended the analysis to include the normal distribution ordinary means and standard deviations of the sum of the DALYs for 296 SEs. Finally, using the relationships presented by Spandaro & Rabl (2008) for lognormal distributions, the geometric mean, μ_g (which for lognormal distributions is equal to the median), and geometric standard deviation, σ_g, were determined for the total DALYs for each of the 296 SEs. As described by Spadaro and Rabl (2008), this allows the 68% CI [μ_g/σ_g , $\mu_g\sigma_g$] and 95% CI [$\mu_g/\sigma^2{}_g$, $\mu_g\sigma^2{}_g$] to be calculated. Spadaro and Rabl recommend showing confidence intervals for pollution damage costs of 1 standard deviation (68% CI) as is the practice in the physical sciences rather than the 95% CI typical of epidemiology and the social sciences. To provide a fuller appreciation of the magnitude of the uncertainty of the DALY values, all four metrics: the mean, median, upper 68% CI and upper 95% CI of the median are calculated.

Eqns. 3.14 and 3.15 are combined and added to the natural log (ln) of the additional factors in Eqn 3.7 to obtain the normal central value of $DALYs_i$ as shown in Eqn. 3.18 for each CoC:

$$DALYs_{i,n} = \left[\frac{\partial DALYs_{cancer}}{\partial intake}\right]_{i,n} + ln(ADAF) + \left[\frac{\partial DALYs_{non-cancer}}{\partial intake}\right]_{i,n} + Ln(C_i * V_B * POP * freq * CF) \tag{3.18}$$

To determine the total normal standard deviation, the square root of the sum of the squares of the standard deviation of the normally distributed cancer combined damage and effect factor shown in Eqn. 3.16 combined with the ln of the ADAF factor from Eqn. 3.7 and the standard deviation of the normally distributed non-cancer damage and effect factor shown in Eqn. 3.17 as shown in Eqn. 3.19:

$$\sigma_{i,tot,n} = \sqrt{\left(\sigma_{\frac{\partial DALYS_{cancer,i,n}}{\partial Intake}} + ln(ADAF)\right)^2 + \left(\sigma_{\frac{\partial DALYS_{non-cancer,i,n}}{\partial Intake}}\right)^2} \qquad (3.19)$$

The exponents of the normally distributed $DALYs_{i,n}$ and $\sigma_{i,tot,n}$ are the lognormal distributions of $DALYs_{i,g}$ and $\sigma_{i,tot,n}$ as shown in Eqns. 3.20 and 3.21:

$$DALYs_{i,g} = e^{DALYs_{i,n}} \qquad (3.20)$$

$$\sigma_{i,g} = e^{\sigma_{i,n}} \qquad (3.21)$$

The individual $DALYs_{i,g}$ are the geometric mean of the lognormally distributed $DALYs_i$ for each CoC while the $\sigma_{i,g}$ is the geometric standard deviation of each CoC. The ordinary mean and standard deviations of the lognormally distributed DALYs are required in order to combine the $DALYs_i$ of mixtures without creating very large $\sigma_{mix,_{i,g}}$. The correlations in Eqns. 3.22 and (3.23) (modified from Eqns. 16 and 17 in Spadaro and Rabl (2008)) are used to find the ordinary mean, μ_i and standard deviation σ_i in DALYs for the lognormal distribution from the $DALYs_{i,g}$ and $\sigma_{i,g}$, which are the geometric mean and standard deviation, respectively. The ordinary means are summed over all i of the mixture as shown in Eqn. 3.24, which gives the ordinary mean of the DALYs of the mixture, $DALYs_{mix,j}$. The ordinary standard deviation of the mixture, $\sigma_{mix,j}$ is obtained from the square root of the squares of the ordinary standard deviations for all i as show in Eqn. 3.25.

$$\mu_i = DALYs_i = DALYs_{i,g} exp^{\left\{\frac{[ln(\sigma_{1,g})]^2}{2}\right\}} \tag{3.22}$$

$$\sigma_i = \mu_i \sqrt{\left({}^{\mu_i}/_{\mu_{i,g}}\right)^2 - 1} \tag{3.23}$$

$$DALYs_{mix,j} = DALYs_1 + DALYs_2 + \cdots DALYs_n \tag{3.24}$$

$$\sigma_{mix} = \sqrt{\sigma_1^2 + \sigma_2^2 + \cdots \sigma_n^2} \tag{3.25}$$

Finally, the $DALYs_{mix,j}$ and $\sigma_{mix,j}$ are transformed to the geometric mean and geometric standard deviation of the lognormally distributed total DALYs of the mixture using Eqns. 3.22 and 3.23 modified to reverse the transformation as shown in Eqn. 3.26 and 3.27.

The key equations used to calculate DALYs, standard deviations, and CI for each SE_j in the database in section 3.3.4 are Eqns. 3.26-3.29.

$$DALYs_{mix,j,g} = {DALYs_{mix,j}} \Big/ {SQRT\left[\left({\sigma_{mix}}/{DALYs_{mix,j}}\right)^2 + 1\right]} \tag{3.26}$$

$$\sigma_{mix,j,g} = exp^{\left\{\left[2*Ln\left({DALYs_{mix,j}}/{DALYs_{mix,j,g}}\right)\right]\right\}} \tag{3.27}$$

Confidence intervals (CI) can be calculated for the 68% and 95% CI as shown in Eqns. 3.28 and 3.29.

$$\text{68\% CI:} \quad [(DALYs_{mix,\ j,g}) \ / \ (\sigma_{mix,j,g}),\ (DALYs_{mix,\ j,g})\ (\sigma_{mix,j,g})] \tag{3.28}$$

$$\text{95\% CI:} \quad [(DALYs_{mix,\ j,g}) \ / \ (\sigma_{mix,j,g})^2,\ (DALYs_{mix,\ j,g})\ (\sigma_{mix,j,g})^2] \tag{3.29}$$

The following assumptions are used in the DALY calculations:

- C_i = concentration of compound “i” is constant for an entire year (Based on 24-hour average concentrations found in the database)
- Population averages are assumed based on Logue (2012):
    - Population Average Age dependent adjustment factor for cancer exposure, ADAF = 1.6
    - Population average fraction of day spent at home = 0.70

3.2.6 Monetary Value of Reducing C_{HCHO} in a Residence

The monetary value (MV) of reducing C_{HCHO} in a residence is shown in Eqn. 3.30

$$HB\$V_{C_{HCHO-A,R} \rightarrow C_{HCHO-B,R}} = \frac{n * DALY\$}{100{,}000} * \left(DALYs_{C_{HCHO-A,R}} - DALYs_{C_{HCHO-B,R}}\right) \qquad (3.30)$$

where,

$HB\$V_{C_{HCHO-A} \rightarrow C_{HCHO-B}}$ = health based monetary value of reducing the Annual average concentration of HCHO in a house from C_{HCHO-A} to C_{HCHO-B}, [$]

C_{HCHO-A} = annual average C_{HCHO} at condition A (ventilation toASHRAE 62.2-2016), [ppb]

C_{HCHO-B} = annual average C_{HCHO} at condition B, [ppb]

n = # of people living in the house, [persons]

DALY$ = value of a DALY, [$/y]

DALYs-$C_{HCHO-A,R}$ = DALYs lost at a given level of risk $_R$, for C_{HCHO-A}

DALYs-$C_{HCHO-B,R}$ = DALYs lost at a given level of risk $_R$, for C_{HCHO-B} [DALYs/100,000 person]

$_R$ = level of risk:

med = median;

ub68%CI = upper bound 68% CI;

ub95%CI = upper bound 95% CI

The health based monetary value of reducing the C_{HCHO} in a residence is off-set by: any additional energy used, the cost of energy and any societal cost of carbon associated with that energy as shown in Eqn. 3.31.

$$\$V_{tot,\ C_{HCHO-A} \rightarrow C_{HCHO-B}} = HB\$V_{C_{HCHO-A} \rightarrow C_{HCHO-B}} - [\Delta E_{A \rightarrow B} \times (1 + SCC)](1 + SCC) - \Delta CC_{ann} - \Delta Maint_{ann} \tag{3.31}$$

where,

$\$V_{tot,\ CHCHO\text{-}A \rightarrow C_{HCHO\text{-}B}}$ = total monetary value of reducing the C_{HCHO}, [$/y]

ΔE = additional energy used in a year under condition B, [kWh/yr]

SCC = societal cost of carbon, [¢/kWh]

ΔCC_{ann} = annualized increase in capital cost of equipment and installation to produce condition B rather than condition A, [$/yr]

$\Delta Maint_{ann}$ = annualized additional cost of maintenance to maintain equipment in condition B rather than condition A, [$/yr]

By setting $\$V_{tot,\ CHCHO\text{-}A \rightarrow C_{HCHO\text{-}B}} = 0$ in Eqn. 3.31 and rearranging, the maximum annualized additional capital cost and maintenance cost $[(\Delta CC_{ann} - \Delta Maint_{ann})_{max}]$

that can be justified by the health based value of the reduction of C_{HCHO}, can be calculated as shown in Eqn. (3.32).

$$(\Delta CC_{ann} - \Delta Maint_{ann})_{max} = HB\$V_{C_{HCHO-A} \rightarrow C_{HCHO-B}} - [\Delta E_{A \rightarrow B} \times (1 + SCC)] \qquad (3.32)$$

3.3 Results and Discussion

3.3.1 Database

Samples were obtained from four geographic regions in the U.S. as well as two regions in Canada. The distribution of samples by geographic region in the U.S. and Canada are shown in Table 3.2.

Table 3.2: Distribution of Samples by Geographic Regions/Divisions

Region[1]			Division[2]		
		296			296
Northeast	**NE**	23	**NE**	CT, ME, MA, NH, RI, VT	11
			MA	NJ, NY, PA	12
Midwest	**MW**	46	**ENC**	IL, IN, MI, OH, WI	39
			WNC	SD	7
South	**S**	203	**SA**	SC, VA, WV	56
			ESC	AL, KY, MS, TN	16
			WSC	AR, LA, OK, TX	131
West	**W**	22	**M**	UT, WY	12
			P	AK, CA, HI, OR, WA	10
Canadian Regions				**Canadian Provinces**	
Ontario	**ON**	1	**ON**	ON, Canada	1
Prairies	**PRR**	1	**AB**	AB, Canada	1

[1]U.S. Geographical Regions: Northeast (NE); Midwest (MW); South (S); and West (W)
[2]U.S. Geographical Divisions: Northeast (NE); Mid Atlantic (MA); East North Central (ENC); West North Central (WNC); South Atlantic (SA); East South Central (ESC); West South Central (WSC); Mountain (M); Pacific (P)

A total of 249 houses are represented in the database. A total of 296 sampling events (SE) were obtained from a total of 340 samples in the database. Single Sampling Event Houses (SSEH) included 215 of the 249 houses (86.4%) and accounted for 215 of the 296 SEs (73%) and 234 of the 340 samples (69%) in the database. Multiple sampling event houses (MSEH) included 34 of the 249 houses (13.6%) and accounted for 81 of the 296 SEs (27%) and 106 of the 340 samples (31%) in the database. Table 3.3 provides details of the number of houses, SEs, and samples from both single and multiple sampling event houses included in the database.

Table 3.3: Number of houses, sampling events, and samples in database

# Houses	SSEH	**215**	MSEH	**34**	**Total # Houses**	**249**
# SEs	from SSEH	**215**	From MSEH	**81**	**Total # SEs**	**296**
# Samples	from SSEH	**234**	From MSEH	**106**	**Total # Samples**	**340**
SSEH:	**# SEs / # SSEH**	**# Samples/SE**		**# samples**		
	199	**1**		**199**		
	13	**2**		**26**		
	3	**3**		**9**		
	215			**234**		
MSEH:	**# SEs**	**# Samples/SE**		**# samples**		
	63	**1**		**63**		
	14	**2**		**28**		
	2	**3**		**6**		
	1	**4**		**4**		
	1	**5**		**5**		
	81			**106**		
	# MSEH	**# SE / MSEH**	**# SE**			
	25	2	50			
	7	**3**	21			
	1	**4**	4			
	1	**6**	6			
	34		81			

A total of 660 compounds at concentrations ≥ 1 μg/m^3 were identified in the Matrix database. Of the 114 compounds that occurred in >5% of the SEs, 111 (94%) had TCEQ ESLs based on the 2015 TCEQ list (TCEQ, 2015)[3].

The assumption that SEs from MSEH are independent, as they are taken at different times after some form of remediation to the indoor environment, is supported by the C_{HCHO} from the 34 MSEH as shown in Figure 3.1. The C_{HCHO}

[3] A summary of database SEs are shown in Appendix B. Details of occurrence of the 114 compounds that occurred in >5% of the SEs for all 296 SEs is available in Microsoft Excel format from the author upon request.

from the different SEs in the same house in Fig. 3.1 are significantly different as expected after remediation.

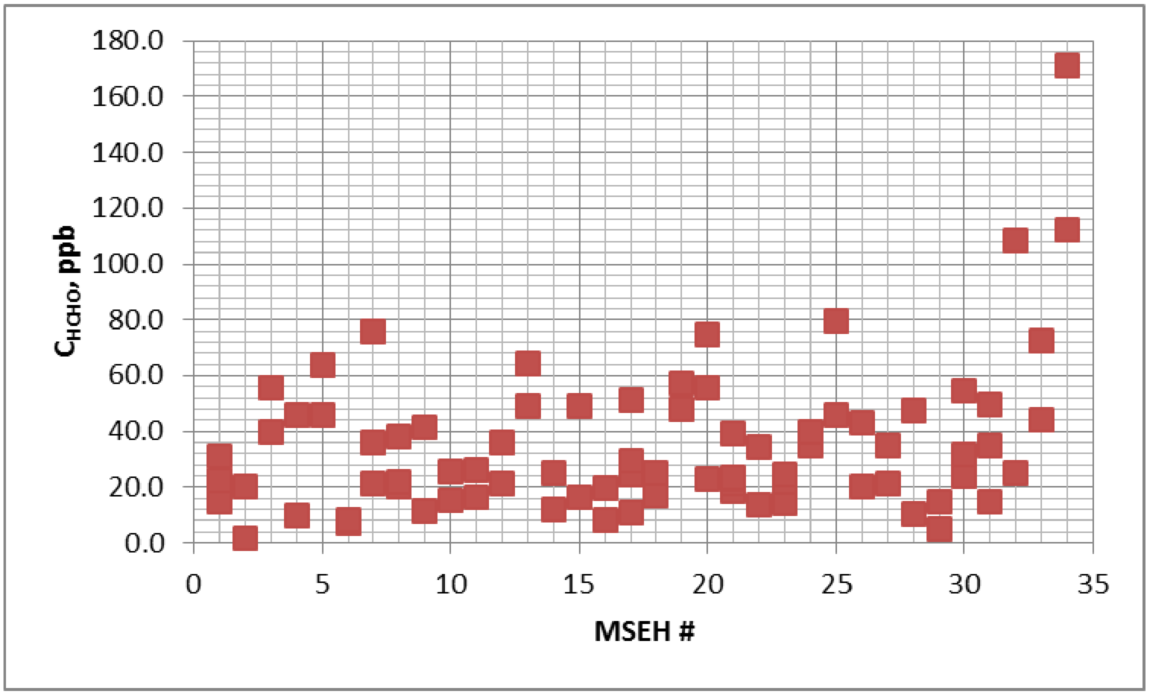
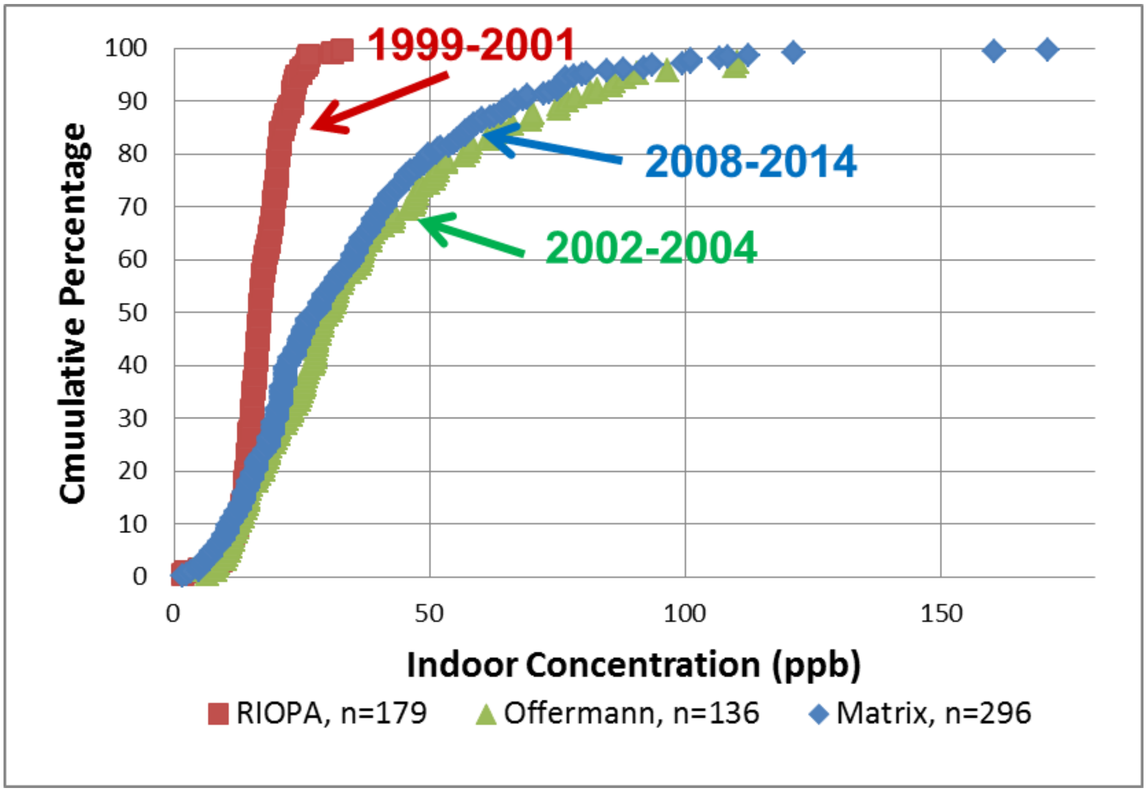


Figure 3.1: C_{HCHO} from separate SEs in Multiple Sampling Event Houses

The distribution of HCHO in the Matrix Database is compared with the HCHO data from the RIOPA study as summarized by Hun et al. (2010) and a database for California homes (Offermann, 2009) in Figure 3.2.



	n	Avg	Min	Max	5th %	25th%	50th%	75th%	95th%
Matrix	296	35	2	171	8	19	28	45	79
RIOPA	179	17	2	33	10	15	17	20	24
Offermann	136	36	4	110	11	19	30	50	90

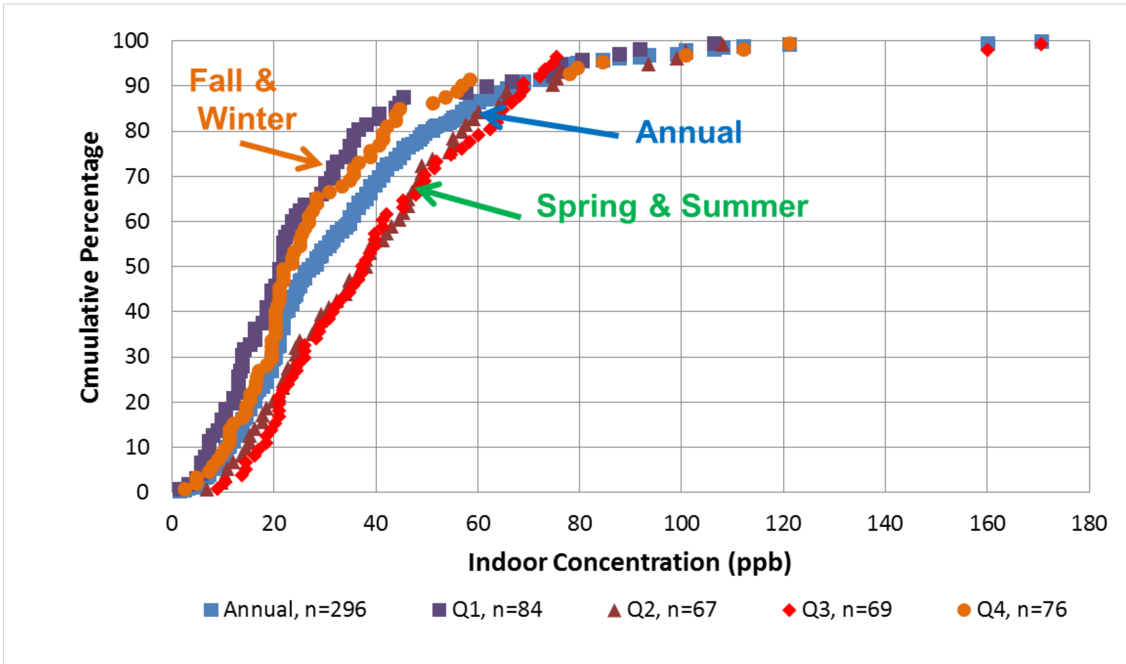
Figure 3.2: Cumulative Dist. of C_{HCHO}: Matrix, Offermann and RIOPA databases

The median C_{HCHO} in the RIOPA study was 17 ppb compared to the 28 ppb median concentration in the Matrix Database. As anticipated, there were more homes at higher concentrations (homes where an IAQ issue was suspected) and more at lower concentrations (homes that had been remediated) in the Matrix Database than in the Offermann database, which reported on only new homes.

The fact that the Matrix and Offermann databases taken from significantly different housing stocks in different parts of the country are so similar is coincidental but remarkable. Both show significantly higher C_{HCHO} than observed in the RIOPA Database, which may be due to an older housing stock in the RIOPA study. House age is unknown in the Matrix database.

Figure 3.3 shows the seasonal cumulative distribution of HCHO in the Matrix Database. As anticipated, C_{HCHO} is higher in the spring and summer than in the fall and winter, likely due to higher temperatures and, thus, higher HCHO emission rates.

Figures 3.4-3.6 show the C_{HCHO} frequency distributions (histograms) for the RIOPA, Offermann and Matrix Databases, respectively. The RIOPA database has a normal distribution while both the Offermann and Matrix databases appear lognormal.



	n	Avg	Min	Max	5^{th} %	25^{th}%	50^{th}%	75^{th}%	95^{th}%
Annual	296	35	2	171	8	19	28	45	79
Q1 - J.F.M	84	27	2	107	6	13	22	35	77
Q2 - A, M, J	67	40	7	108	11	22	38	54	94
Q3 - J,A,S	69	43	9	171	15	23	37	55	75
Q4 - O,N,D	76	31	2	121	8	17	23	39	83

Figure 3.3: Seasonal HCHO Cumulative Distribution

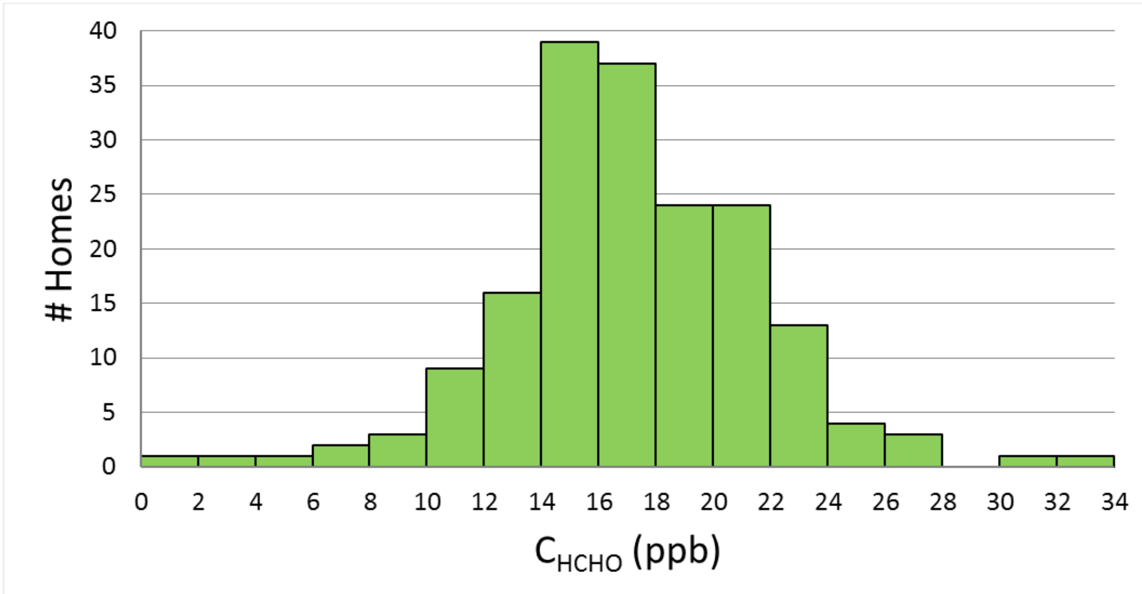


Figure 3.4: C_{HCHO} Frequency Distribution of RIOPA Database

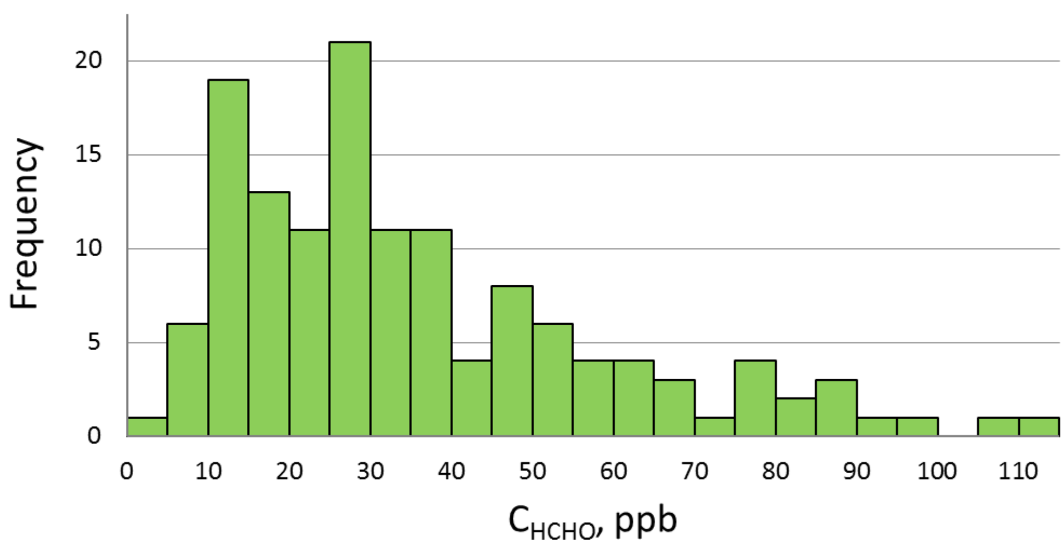


Figure 3.5: C_{HCHO} Frequency Distribution of Offermann Database

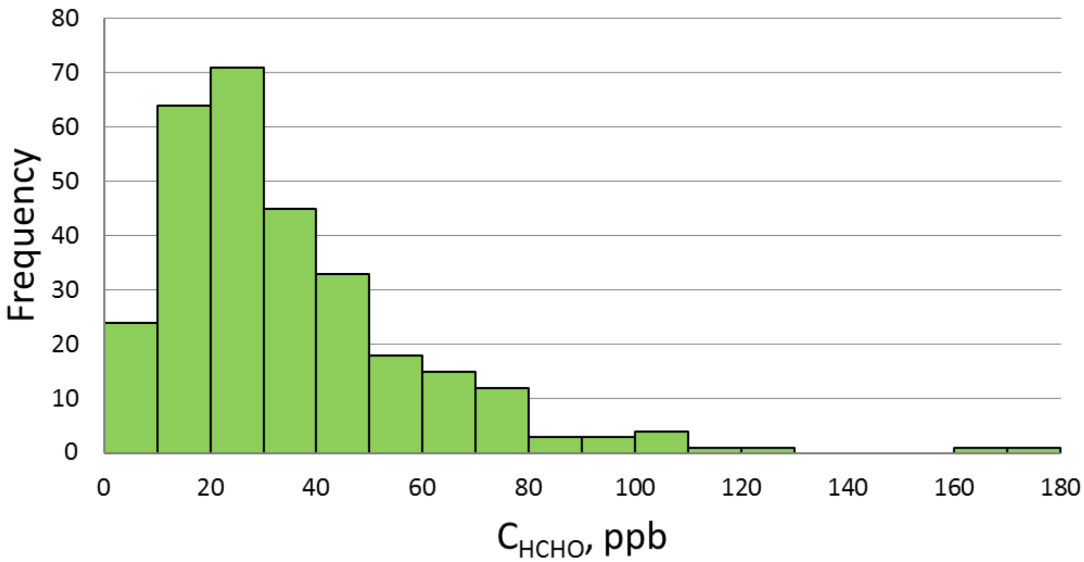


Figure 3.6: C_{HCHO} Frequency Distribution of Matrix Database

3.3.2 Contaminants of Concern

A total of 660 unique compounds (CAS #) were identified in the 340 datasets provided by Matrix at concentrations > 1 μg/m^3. Of these, more than 420 (64%) are on the TCEQ 2015 Effects Screening Levels (ESL) list used in the review of air permitting data (TCEQ, 2015). A total of 114 unique compounds (CAS#) were present in at least 5% of the 249 sampling events (SEs). Of these, 111 (97%) are on the TCEQ 2015 ESL List and were assigned a reference concentration (C_{ref_i}) equivalent to the lower of the short term (1 hour) or long-term (annual average) effects screening level (ESL_{ST} / ESL_{LT}).

The 114 compounds present in >5% of homes were screened for compounds on the lists shown in Table 3.1 and Table 3.4. Of interest is that 61% of the compounds found in these homes are fragrance ingredients. In addition, 34% of the compounds found in the homes are Gasoline Range Organics (GROs) comprised of C6-C10 alkanes. These GROs are likely associated with attached garages, which may be reduced relatively easily by ventilating the garage under negative pressure with respect to the house and sealing the wall(s) and door between the house and the attached garage.

Table 3.4: Compounds on Criteria Lists in Database

Criteria No.	Criteria	# Cmpds in >5% of SEs	% of Cmpds in >5% of SEs
1	On 2015 TCEQ ESL list	111	97%
2	Asthmagens	11	9%
3	Neurotoxicants		
3a	Neurotoxicants	13	11%
3b	Developmental Neurotoxicants	2	2%
4	Fragrance	71	$\boxed{61\%}$
5	ATSDR – Chronic Value	14	12%
6	CA OEHHA, REL_C	12	10%
7	CA OEHHA Prop 65		
7a	Prop 65 – Cancer	11	9%
7b	Prop 65 -Developmental	3	3%
8	CA OEHHA NSRL / MADL	8	7%
9	GRO (Gas Range Organics)	39	$\boxed{34\%}$
10	DALY Damage and Effect Factors		
10a	$\left[{\partial DALYS_{cancer}}/{\partial intake}\right]$	16	14%
10b	$\left[{\partial DALYS_{non-cancer,inh}}/{\partial intake}\right]$	15	13%

A list of the 114 compounds found in >5% of SEs is provided in Table 3.5. Compounds tabulated by criteria list Table 3.4 are annotated by criteria number in Table 3.5. The nine compounds identified with a * and heavy cell borders in Table 3.5 are found in >5% of the SEs above the C_{ref_i} and are taken as the only contaminants of concern (CoC) as defined in this work.

Aldehydes are present in all SEs. Formaldehyde and acetaldehyde are present in 100% of the samples. Seven other aldehydes (hexaldehyde, valeraldehyde, benzaldehyde, butyraldehyde, propionaldehyde, nonyl aldehyde, and tolualdehyde) are present in a majority of SEs.

Acetic acid is present in more than 90% of the SEs and is of interest due to its' impact on corrosion of copper air conditioning evaporator coils. The increased presence/concentration of acetic acid in homes is one of the drivers behind the HVAC industry moving to aluminum evaporator coils to replace copper coils.

The TCEQ 2015 ESL list introduced a generic fragrance category with a long-term ESL of 100 $\mu g/m^3$. This new category was used for 2-pentyl furan, estragole, and p-cymenene which were previously not categorizable using the TCEQ list. In addition, the fragrance category was used for α-cedrine and sabinene, which were previously categorized as "alkenes (C10-C16) not otherwise specified". All five compounds are on the International Fragrance Association (IFRA) list of fragrance ingredients (IFRA, 2011). Of the three previously uncategorized fragrances, only estragole is considered further. Estragole is the only one of these three fragrances that has DALY parameters from Huijbregts, et al. (2005) . Estragole is considered in calculating the known DALYs in each SE in Section 3.4.4.

Table 3.5: Compounds in Database occurring in >5% of SEs

Compound[Criteria Nos. - Table 3.4]	*CAS#*	*Incidence (% SEs)*	*Median (μg/m³)*	*CV*	*C_{ref} (μg/m³)*	*%>C_{ref}*
18 Compounds in >50% of SEs; 7 with DALY data; 100% with TCEQ ESLs; 5 with 5%> C_{ref}						
*Formaldehyde[1,2,5,6,7a,8,10a]	50-00-00	100%	34	0.7	9[a]	96.3%
*Acetaldehyde[1,2,4,6,7a,8,10a&b]	75-07-0	100%	18	1.3	45	15.6%
Toluene[1,2,3a,3b,5,6,7b,8,9,10a&b]	108-88-3	93.9%	7	2	300[a]	0.0%
Hexaldehyde[1,4,]	66-25-1	93.6%	10	2.2	330	2.9%
*Acetic Acid[1,2,4]	64-19-7	91.2%	27	1.7	25	50.9%
*Limonene[1,2,4,10a]	5989-27-5	89.9%	12	2.0	110	6.9%
Valeraldehyde[1,4]	110-62-3	87.2%	4	1.9	98	2.2%
α-Pinene[1,4]	80-56-8	85.8%	8	3	350	2.8%
o, m, p – Xylene[1,4,5,6,9,10a&b]	1330-20-7	83.4%	5	2	180	1.0%
*Benzaldehyde[1,4,10a]	100-52-7	80.7%	2	1.4	9	9.2%
Butyraldehyde[1,4]	123-72-8	79.7%	2	1.7	27	3.7%
*Propionaldehyde[1,2,4]	123-38-6	70.6%	2	1.9	40	1.4%
Nonyl Aldehyde[1,4]	124-19-6	64.5%	3	1.7	150	0.0%
Decane[1,4,9]	124-18-5	60.8%	1	5	1000	0.0%
β-Pinene[1,4]	127-91-3	57.8%	1	3.2	350	0.4%
Tolualdehyde[1]	529-20-4	55.7%	1	2.1	9	1.4%
Acetone[1,3a,4,5]	67-64-1	54.4%	2	4.7	4800	0.0%
Ethyl Alcohol[1,3a,3b,4,10a]	64-17-5	54.0%	0.5	4.3	1880	0.0%
23 Compounds in >25-50% of SEs; 4 with DALY data; 96% with TCEQ ESLs; 1 with 5%> C_{ref}						
Tetradecane[1,4]	629-59-4	48.0%	0	2.9	350	0.0%
Dodecane[1,4]	112-40-3	46.6%	0	3.9	350	0.0%
Ethyl Benzene[1,5,6,7a,8,9,10a&b]	100-41-4	46.3%	0	3.9	570	0.0%
Isopropyl Alcohol[1,4,6]	67-63-0	45.9%	0	3.4	492	0.2%
Isopentane[1,9]	78-78-4	45.3%	0	7.4	7100	0.0%
*Benzene[1,2,3a,5,6,7a,7b,8,9,10a&b]	71-43-2	44.3%	0	3.4	3.0[a]	19.0%
n-Butyl Acetate[1,4]	123-86-4	43.9%	0	3.0	1400	0.0%
Heptaldehyde[1,4]	111-71-7	43.2%	0	3.5	40	0.5%
n-Hexane[1,3a,4,5,6,9,10b]	110-71-7	41.2%	0	3.1	200	0.0%
n-Pentane[1,9]	109-66-0	38.2%	0	2.8	7100	0.0%
Ethyl Acetate[1,3a,4]	141-78-6	38.2%	0	2.9	1440	0.0%
Camphene[1,4]	79-92-5	36.8%	0	3.3	100	0.6%
Nonane[1,4,9]	111-84-2	36.5%	0	4.9	1050	0.0%
n-Octane[1,9]	111-65-9	36.1%	0	2.9	350	0.0%
Tridecane[1,4]	629-50-5	34.1%	0	3.0	350	0.0%
2-Methyl Pentane[1,9]	107-83-5	31.8%	0	3.5	350	0.0%
Methyl Amyl Ketone[1,4]	110-43-0	31.1%	0	2.7	840	0.0%
Naphthalene[1,4,5,6,71,8,9,10a&b]	91-20-3	29.7%	0	3.1	9[a]	4.8%
n-Heptane[1,4,9]	142-82-5	27.7%	0	3.5	350	0.0%
Glycol Ether – EB[1]	7795-91-7	27.4%	0	3.3	36	0.4%
2-Pentyl Furan[4]	3777-69-3	25.7%	0	3.8	100	0.0%

* Compounds found in >5% of the SEs above the $Cref_i$

[a] CA OEHHA REL is used when less than TCEQ ESL

Table 3.6: Compounds in Database occurring in >5% of SEs, continued

Compound[Criteria Nos. - Table 3.4]	***CAS#***	***Incidence (% SEs)***	***Median ($\mu g/m^3$)***	***CV***	***C_{ref} ($\mu g/m^3$)***	***%>C_{ref}***
Undecane[1,4]	1120-21-4	25.3%	0	5.5	350	0.2%
b-Phellandrene[1,4,9]	555-10-2	25.0%	0	3.9	200	0.8%
8 Compounds in >20-25% of SEs; 1 with DALY data; 87% with TCEQ ESLs; 2 with 5%> C_{ref}						
Octylaldehyde[1,4]	124-13-0	24.0%	0	3.7	150	0.0%
Methyl Ethyl Ketone[1,3a,4,10b]	78-93-3	24.0%	0	4.2	2600	0.0%
Bis trimethylsilyl Salicylic Acid	3789-85-3	23.3%	0	3.9	No C_{Ref}	No C_{Ref}
n-Butane[1]	106-97-8	23.0%	0	3.7	7200	0.0%
Crotenaldehyde[1]	4170-30-3	22.3%	0	2.7	3.2	3.0%
Linalool[1,4]	78-70-6	22.0%	0	4.7	200	0.0%
*d-Carene[1,2,4]	13466-78-9	20.9%	0	4.0	112	5.4%
p-Ethyltoluene[1]	622-96-8	20.9%	0	3.5	125	0.0%
*Decyl Aldehyde[1,4]	112-31-2	20.6%	0	2.8	4	7.5%
31 Compounds in >10-20% of SEs; 5 with DALY data; 97% with TCEQ ESLs; 1 with 5%> C_{ref}						
Hexanoic Acid[1,4]	142-62-1	19.9%	0	3.2	30	0.0%
Isopropyltoluene[1,4]	99-87-6	19.3%	0	6.6	275	0.4%
Styrene[1,2,3a,4,5,6,7a,10a&b]	100-42-5	18.9%	0	5.5	110	0.0%
Pentadecane[1,4]	629-62-9	18.9%	0	3.2	350	0.0%
3-Methyl Pentane[1,9]	96-14-0	18.9%	0	3.2	350	0.0%
2,4-Dimethylpentane-3-one[1]	565-80-0	18.6%	0	2.9	230	0.0%
Furfuraldehyde[1,4,10a]	98-01-1	17.9%	0	3.0	8	2.4%
Methyl Isobutyl Ketone[1,3a,4,7a,7b,10b]	108-10-1	17.6%	0	3.8	82	0.0%
Octamethyl-Cyclotrisiloxane[1]	556-67-2	17.6%	0	5.9	100	0.6%
1,2,4-Trimethylbenzene[1,4]	95-63-6	16.6%	0	3.9	54	0.0%
Acetophenone[1,4]	98-86-2	16.6%	0	3.5	49	0.0%
Glycol Ether DPM[1,]	34590-94-8	16.2%	0	4.9	310	0.0%
2-Methyl Hexane[1,9]	591-76-4	15.2%	0	3.7	307	0.0%
2-Methyl-2-Propenoic Acid	760-93-0	15.2%	0	3.8	No C_{Ref}	No C_{Ref}
Myrcene[1,4,7a]	123-35-3	14.9%	0	3.9	30	0.0%
2,2,4-Trimethylpentane[1,9]	540-84-1	14.2%	0	5.8	350	0.0%
n-Butanol[1,4]	71-36-3	13.5%	0	4.5	61	0.1%
Eucalyptol[1,4]	470-82-6	13.2%	0	3.7	26	0.0%
n-Hexadecane[1,4]	544-76-3	13.2%	0	6.2	350	0.0%
2,2,5-Trimethyl Hexane[1,4,9]	3522-94-9	12.2%	0	6.2	350	0.0%
1,3,5-Trimethylbenzene[1,4,9]	108-67-8	11.8%	0	8.3	54	0.5%
Hexamethyl-Cyclotrisiloxane[1]	541-05-9	11.8%	0	6.0	100	0.0%
Propyl Benzene[1,9]	103-65-1	11.5%	0	4.9	250	0.0%
2-Isopropyl Toluene[9]	26444-18-8	11.5%	0	6.6	245	0.0%
Glycol Ether EB[1,4,5,10b]	111-76-2	10.8%	0	8.2	2900	0.0%
Cyclohexane[1,3a,9,10b]	110-82-7	10.5%	0	8.7	340	0.0%

Table 3.7: Compounds in Database occurring in >5% of SEs, continued

Compound[Criteria Nos. - Table 3.4]	*CAS#*	*Incidence (% SEs)*	*Median ($\mu g/m^3$)*	*CV*	*C_{ref} ($\mu g/m^3$)*	*%>C_{ref}*
Propylene Glycol[1,4]	57-55-6	10.5%	0	4.3	156	0.0%
1,2,4,5-tetraethylbenzene[1,9]	95-93-2	10.5%	0	4.4	245	0.0%
*Camphor[1,4]	76-22-2	10.1%	0	4.2	2	7.2%
Dimethyl Hexane[1,9]	590-73-8	10.1%	0	5.9	350	0.0%
35 Compounds in >5-10% of SEs; 5 with DALY data; 94% with TCEQ ESLs; 0 with 5%> C_{ref}						
n-Butyl Butyrate[1,4]	109-21-7	9.8%	0	8.0	300	0.0%
2-Ethyltoluene[1]	611-14-3	9.8%	0	7.3	125	0.5%
Octanoic Acid[1,4]	124-07-2	9.8%	0	3.7	59	0.0%
2.6-Dimethyl Undecane[1]	17301-23-4	9.8%	0	6.3	350	0.0%
Propanoic acid, 2-methyl, 3-hydroxy-2,4,4-trimethylpentyl ester (Texanol B)	74367-34-3	9.8%	0	5.3	No C_{Ref}	No C_{Ref}
Cyclohexanone[1,3a,4]	108-94-1	9.5%	0	3.9	80	0.0%
Menthol[1,4]	89-78-1	9.5%	0	5.7	234	0.0%
Estragole[1,4,6,7a,10a]	140-67-0	9.1%	0	5.3	100	0.0%
1-Butoxy-2-Propanol[1,4]	5131-66-8	8.1%	0	6.5	73	0.0%
Benzyl Alcohol[1,3a,4]	100-51-6	7.8%	0	4.4	44	0.0%
o-Cymene[1]	527-84-4	7.8%	0	56.8	275	0.0%
3-Methyl Hexane[1,9]	589-34-4	7.1%	0	5.4	307	0.0%
Isobutyl Alcohol[1,4]	78-83-1	7.1%	0	7.8	152	0.0%
2,4-Dimethyl Pentane[1,9]	108-08-7	6.8%	0	8.0	350	0.0%
α-Cedrine[1,4]	469-61-4	6.8%	0	5.3	100	0.0%
2,3,4-Trimethyl Pentane[1,9]	565-75-3	6.8%	0	7.2	350	0.0%
2,6,7-Trimethyl Decane[1]	62108-25-2	6.8%	0	6.1	350	0.0%
Methyl Acetate[1,4]	79-20-9	6.8%	0	8.7	600	0.0%
1,4-Dichlorobenzene[1,5,6,7a,8,10a&b]	106-46-7	6.4%	0	10.8	160	0.1%
p-Cymenene[4]	1195-32-0	6.4%	0	5.9	100	0.0%
Methyl Salicylate[1,4]	119-36-8	6.1%	0	11.0	5	1.6%
Nonanoic Acid[1,4]	112-05-0	6.1%	0	7.0	64	0.0%
1,2-Dichloroethane[1,5,7a,8,10a]	107-06-2	5.7%	0	6.2	4	3.3%
1-Chloro-4(Trifluoromethyl)-Benzene[1]	98-56-6	5.7%	0	10.9	183	0.8%
Methyl Cyclohexane[1]	108-87-2	5.7%	0	6.1	1610	0.0%
Isoamyl Alcohol[1,4]	123-87-2	5.7%	0	5.5	73	0.0%
4-Methyl Heptane[1,9]	589-53-7	5.7%	0	5.5	350	0.0%
3-Ethyl-2-Methyl-Pentane[1,9]	609-26-7	5.7%	0	6.5	350	0.0%
2-Methyl Decane[1,9]	6975-98-0	5.7%	0	10.4	350	0.0%
2-ethyl-1-Hexanol[1,4,10a]	104-76-7	5.4%	0	4.6	160	0.0%
1-Heptanol[1,4]	111-70-6	5.4%	0	5.6	270	0.0%
Sabinene[1,4]	3387-41-5	5.4%	0	9.5	100	0.7%
2,5,6-Trimethyl-Octane[1,9]	62016-14-2	5.1%	0	10.1	350	0.0%
Cumene[1,2,3a,7a,10b]	98-82-8	5.1%	0	9.7	250	0.0%

Table 3.6 lists the three compounds found in >5% of the SEs in the database that are not on the TCEQ 2015 ESL list. Bis trimethylsilyl salicylic acid, 2-methyl-2-propanoic acid and Texanol B are not found on any of the criteria lists inTable 3.1.

Table 3.8: Compounds in Database occurring in >5% of SEs without a TCEQ ESL

Compound	**CAS#**	**Incidence (%SEs)**
Bis Trimethylsilyl Salicylic Acid	3789-85-3	23.3%
2-methyl-2-Propanoic Acid	760-93-0	15.2%
Texanol B	74367-34-3	9.8%

3.3.2.1 Incidence of Contaminants of Concern and exceedance of $C_{ref,i}$

The 9 CoC identified in Table 3.5 plus estragole, for a total of 10 CoC, are sorted by the % of SEs where the CoC is > 100% of the $C_{ref,i}$ in Table 3.7.

Only two CoCs (formaldehyde and acetic acid) are present in amounts ≥ $C_{ref,i}$ in more than 50% of the SEs. Two additional CoCs (acetaldehyde and benzene) are present in amounts ≥ $C_{ref,i}$ between 15-20% of the SEs. Finally, there are only six other CoCs (benzaldehyde, decyl aldehyde, camphor, limonene, d-carene and estragole) that are present at concentrations ≥ $C_{ref,i}$ in 5 to 10% of the SEs. Estragole is shown as it is known to be a carcinogen by the State of CA and occurs in >5% of the SEs. Of the 10 CoC identified in the database, 4 (40%) are aldehydes and 3 (30%) are terpenes which can react with ozone to form aldehydes.

Table 3.9**:** 9 CoC plus Estragole

Compound	**Family**	**$C_{ref,I}$ ($\mu g/m^3$)**	**Incidence (% SEs)**	**% SEs > C_{ref}**
Formaldehyde[1]	Ald	9	100%	96%
Acetic Acid	Acid	25	91%	51%
Benzene[1]	Aro	3	44%	19%
Acetaldehyde	Ald	45	100%	16%
Benzaldehyde	Ald	9	81%	9%
Decyl Aldehyde	Ald	4	21%	8%
Camphor	Terp	2	10%	7%
Limonene	Terp	110	90%	7%
d-Carene	Terp	112	21%	5%
Estragole[2,3]	Aro	100	9%	0%

[1] CA OEHHA cREL used

[2] Fragrance classification for TCEQ $C_{ref,I}$ used

[3] Used for DALY calculation only

The prevalence of the 10 CoC with the % of SEs that exceed their $C_{ref,i}$ are compared in Figure 3.7. Even though acetaldehyde, benzaldehyde and limonene occur in >80% of the SEs, they exceed their respective $C_{ref,i}$ in < 20% of SEs.

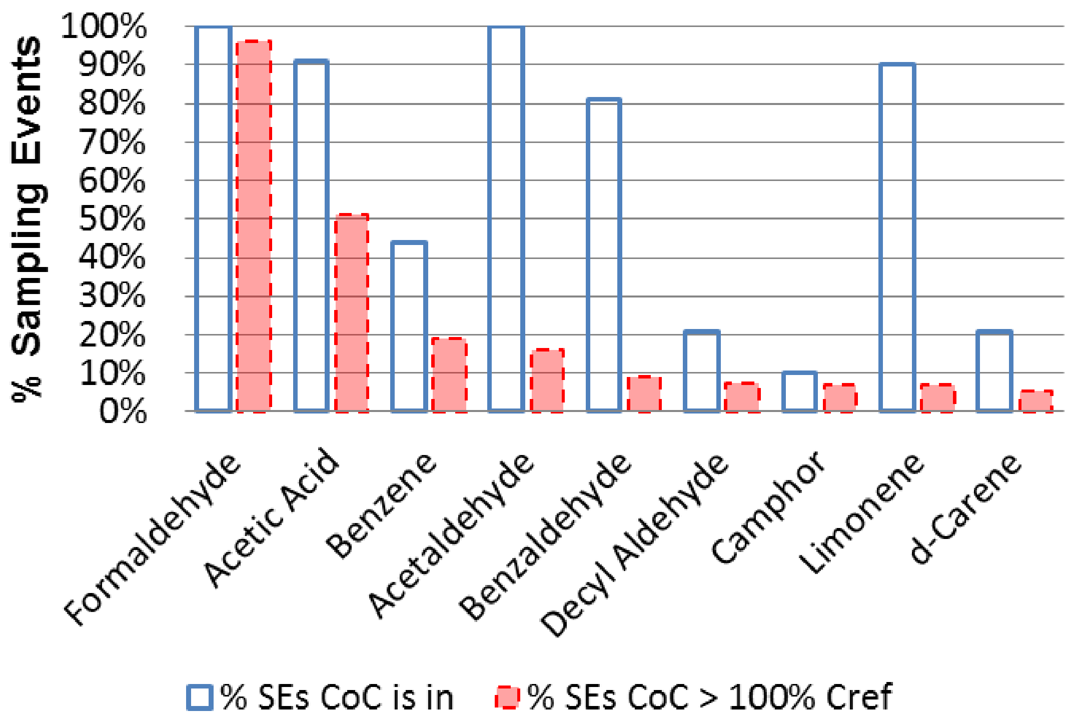


Figure 3.7: Occurrence of CoC vs. Exceedance of $C_{ref,\ i}$ in 296 SEs

3.3.3 Formaldehyde Concentration vs. No. of Contaminants of Concern

The C_{HCHO} vs. # of CoC is another comparison used to evaluate whether C_{HCHO} is a reasonable metric for IAQ in homes.

As shown in Figure 3.8, homes with C_{HCHO} between 1 and 7 ppb had an 87% chance of not having any other contaminant of concern (CoC) other than HCHO above their reference concentrations ($C_{ref,i}$), a 7% chance of having 1 other CoC, and a 7% chance of having 2 other CoCs. Between 8 and 16 ppb, there was a 56% chance of not having any other CoC other than HCHO above their $C_{ref,i}$. At greater than 81 ppb of HCHO, 100% of houses had more than one other CoC other than HCHO above their $C_{ref,i}$. In other words, in houses used in this database, elevated C_{HCHO} appears to be a good metric for the presence of other gaseous CoCs at concentrations above their $C_{ref,i}$. If C_{HCHO} is less than the California OEHHA REL of 7 ppb, the chances of having other CoCs above very conservative threshold values is small. To have 50% or higher chance of having no other CoC other than HCHO above it's $C_{ref,i}$, C_{HCHO} should be kept at or below 16 ppb. To increase this chance to above 80%, C_{HCHO} should be kept at or below the CA OEHHA REL of 7 ppb. A limitation of this database is the limited number of SEs in homes with C_{HCHO} in the range of 1-7 ppb (15 SEs) and >81 ppb (13 SEs).

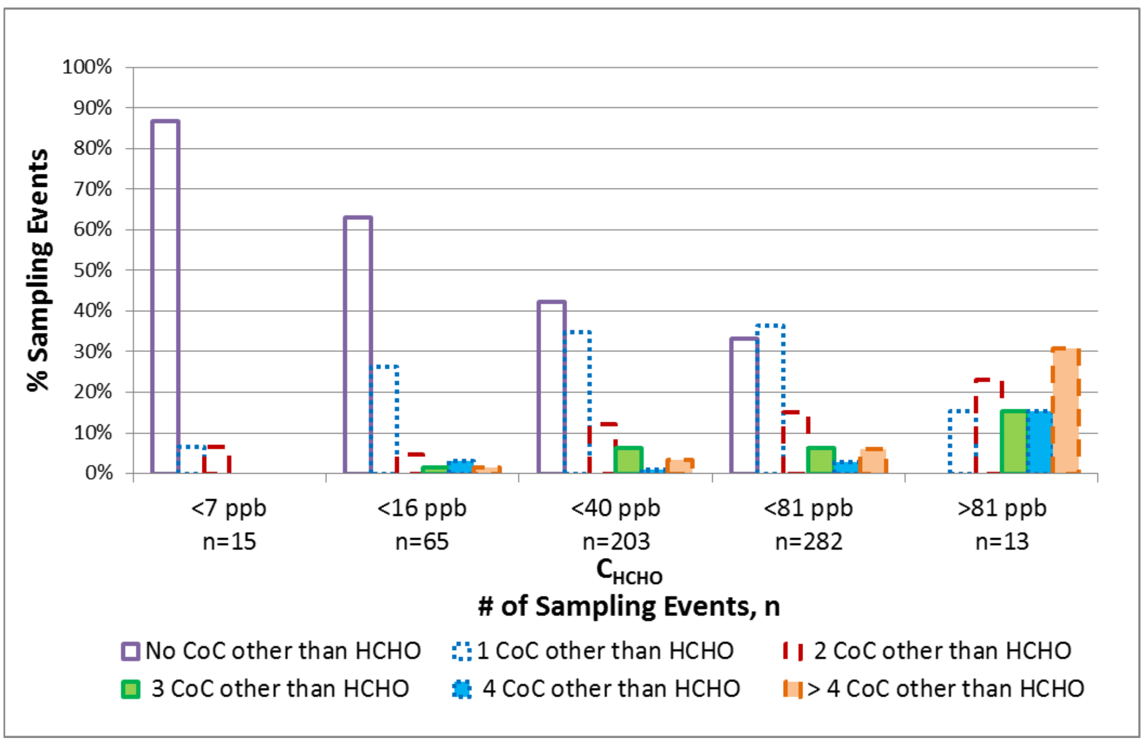


Figure 3.8: C_{HCHO} in bins by Guidelines vs. # CoCs

3.3.4 Correlation of HCHO to other CoC

The correlation of C_{HCHO} with TVOCs + Aldehydes (including HCHO) and the nine additional CoC identified in section 3.4.2 was determined using a Spearman correlation coefficient analysis performed using Excel with a Bonferroni Procedure: number of tests, k=9, significance level, α=0.05; test is statistically significant if $p< 0.0056$.

As shown inTable 3.8, all but Camphor (which occurs in 10% of SEs and exceeds its' C_{ref} in 7% of SEs) correlate well with HCHO. This is one additional confirmation that HCHO is a good surrogate metric for other VOCs, including aldehydes.

Table 3.10: Spearman Correlation Coefficients

Comparison	Correlation of Formaldehyde vs	% Samples Cmpd in	% Samples > C_{ref}	R^2	Fisher 95% CI	p-value
1	TVOCs + Aldehydes	100.00%	68.90%	0.592	0.511 to 0.664	<0.0001
2	Acetic Acid	91.20%	50.90%	0.539	0.450 to 0.617	<0.0001
3	Acetaldehyde	100.00%	15.60%	0.587	0.505 to 0.659	<0.0001
4	Benzene	44.30%	12.40%	-0.18	-0.291 to -0.064	0.0019
5	Benzaldehyde	80.70%	9.20%	0.525	0.434 to 0.605	<0.0001
6	Decyl Aldehyde	20.60%	7.50%	0.184	0.068 to 0.295	0.0015
7	Camphor	10.10%	7.20%	-0.039	-0.156 to 0.078	0.5015
8	Limonene	89.90%	6.90%	0.394	0.290 to 0.488	<0.0001
9	d-Carene	20.90%	5.40%	0.193	0.077 to 0.303	0.0008

3.3.5 Hazard Index (HI)

A Hazard Index (HI) was calculated using Eqn. 3.1 for each of the 296 SE for the 111 compounds with a Cref that and in > 5% of the SEs. The relative frequency distribution of HI based on $C_{ref,HCHO=7\ ppb}$ for the 296 SEs shown in Figure 3.9 is representative of HI distributions with other $C_{ref,\ HCHO=16,\ 40\ and\ 81\ ppb}$, all of which appear lognormal.

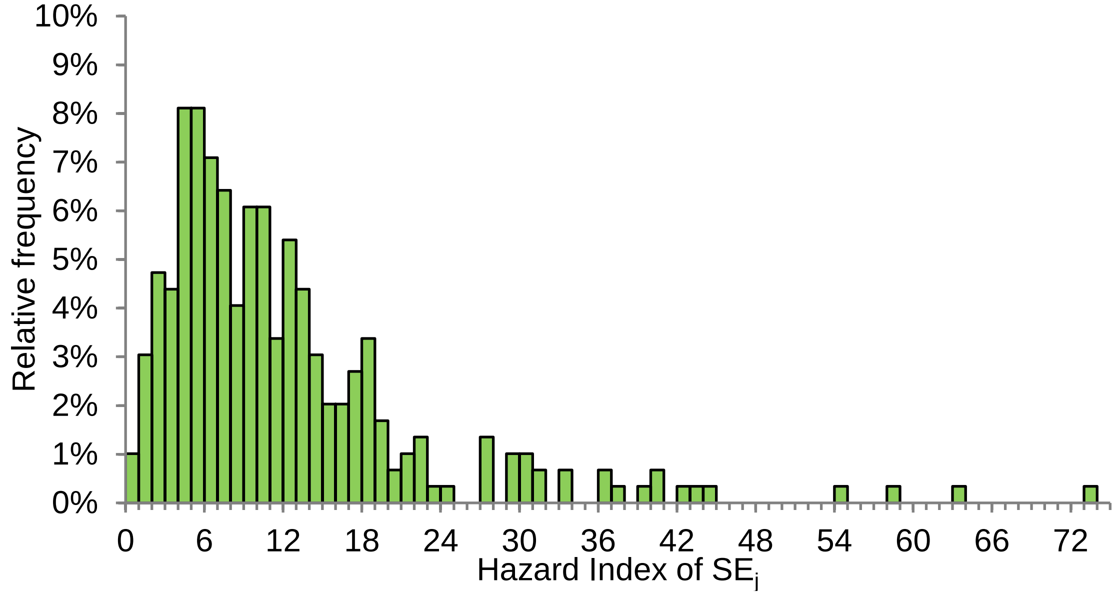
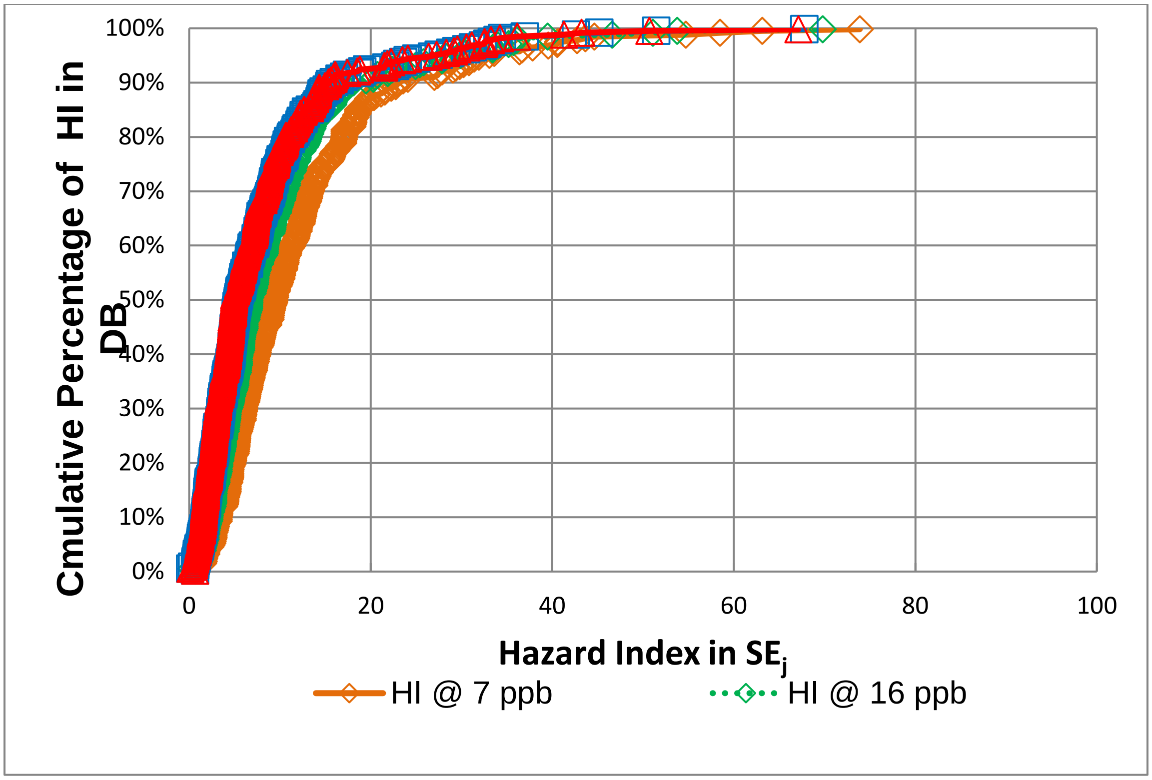


Figure 3.9 Distribution of HI with $C_{ref,\ HCHO=\ 7\ ppb}$

The cumulative distribution for HI of the full database (111 chemicals with a $C_{ref,i}$ and in > 5% of SEs) is shown in Figure 3.10. The lower the choice of $C_{ref,\ HCHO}$ (81, 40, 16, and 7 ppb) the further to the right the cumulative distribution is shifted. When 7 ppb is used as $C_{ref,\ HCHO}$, only 3 of the 296 SE (<1%) have HI ≤ 1. When 81 ppb is used as $C_{ref,\ HCHO}$, only 7 of the 296 SE (~2%) have HI ≤ 1. Note that even at the 5th percentile level, the HI of the sum of just the 9 CoC is > 1 which is the criteria for additional concern or analysis. This indicates that either the choice of $C_{ref,\ i}$ are very conservative, or that additional efforts may be appropriate to reduce exposure to CoC in houses.



	n	Avg	Min	Max	5th %	25th%	50th%	75th%	95th%
HI @ 7 ppb	296	12.1	0.4	73.9	2.5	5.3	9.4	15	32.2
HI @ 16 ppb	296	9.5	0.2	69.8	1.7	3.9	6.7	11.6	28.7
HI @ 40 ppb	296	8.2	0.1	67.8	1.2	3	5.4	10	27
HI @ 81 ppb	296	7.8	0.1	67.1	1.1	2.8	4.9	9.6	26.6

Figure 3.10: Cumulative distribution of HI in Database

To evaluate the impact of individual CoC on the overall HI of the entire DB, the HI of each CoC_i across all SEs was calculated by using Equation 3.4. The five CoC that contribute ≥ 5% to the total HI are shown in Figure 3.11. Of these, only formaldehyde and acetic acid contribute more than 10% of the total HI when

$C_{ref,\ HCHO \leq 40\ ppb}$ is used. When $C_{ref,\ HCHO \geq 40\ ppb}$ is used, acetic acid contributes more of the total HI than formaldehyde.

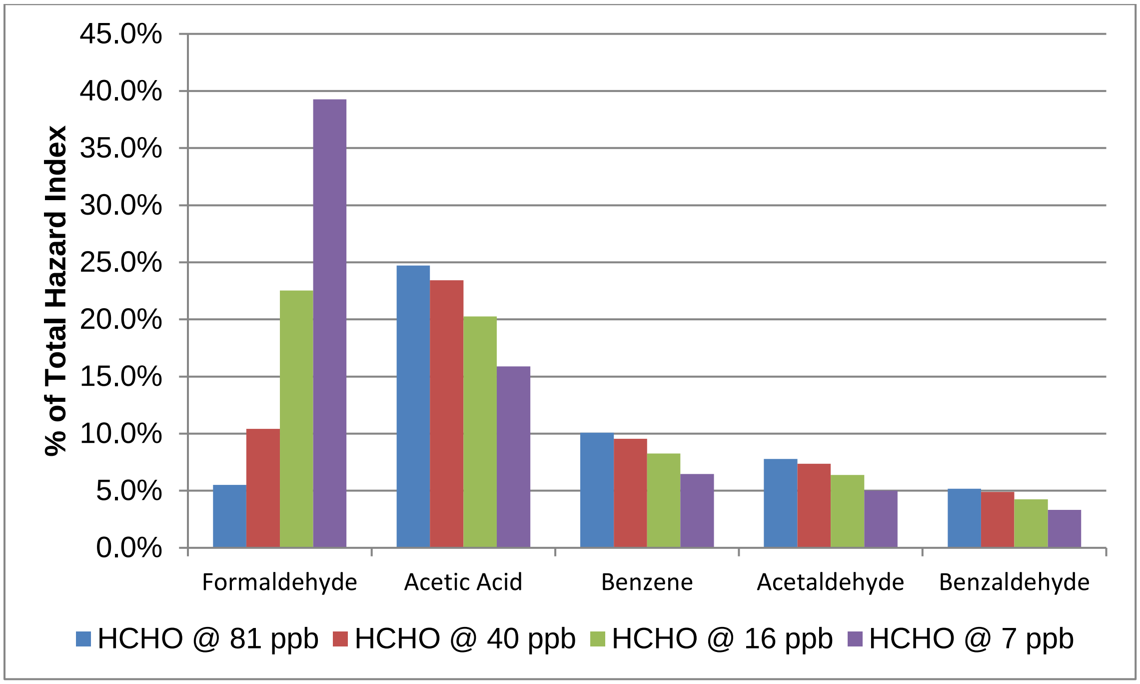


Figure 3.11: Hazard Index distribution of CoC with ≥ 5% of HI

The HI for formaldehyde increases as the C_{ref} for HCHO is decreased from 81 to 7 ppb as the denominator in equation 3.4 decreases. The % of total HI of the other CoC decreases as the % of the total HI of HCHO increases.

The five compounds shown in Figure 3.11 account for 53-70% of the total HI in the database - increasing as the C_{ref} for HCHO goes from 81 to 7 ppb. Formaldehyde dominates the HI, contributing nearly 40% of the HI when the California OEHHA

REL of 7 ppb is used as the reference C_{HCHO}. When higher RELs are used for formaldehyde, acetic acid is the dominant CoC, contributing 20-25% of the total HI in the database - increasing as the C_{ref} for HCHO goes from 16 to 81 ppb.

It is interesting that formaldehyde and acetic acid compete for the 1st or 2nd highest level of HI in this database depending on which C_{ref} for formaldehyde is selected. The unexpected finding that acetic acid contributes significantly to the HI in this database may be due to the increased use of acetic acid based caulks to tighten building envelopes as well as vinegar as the basis of products marketed as "environmentally friendly" cleaning products. Not only may elevated concentrations of acetic acid be a potential health concern, they can also contribute to formicary corrosion of copper, for example in copper air conditioning coils.

The importance of HCHO on the overall hazard index shown in Figure 3.11 is additional evidence that C_{HCHO} can be used as a primary metric for VOCs, including aldehydes in residential applications represented by the database introduced by Jackson et al. (2011a) and expanded on in this study.

3.3.5.1 Contaminants of Concern comprising >5% of HI:

The five CoC shown in Figure 3.11 which contribute >5% of the total HI are briefly discussed here.

Formaldehyde was described in Chapter 2 of this dissertation. Sources of formaldehyde in homes include pressed wood products, combustion sources, certain personal care products, permanent press clothing, and ozone reactions with terpenes. Formaldehyde is a known human carcinogen (IARC, 2004; U.S. DHHS, 2014), a mucous membrane irritant, an allergic sensitizer, and can increase the risk and severity of asthma (CA OEHHA, 2008; Rumchev et al., 2002).

Acetic acid is found in food, wines, cleaning products, pesticides, gasoline, diesel exhaust, smoke from forest fires (U.S. National Library of Medicine, 2016b), and is used in fragrances (IFRA, 2011), household cleaners, as a food preservative and in vinegar (Luttrell, 2012). Acetic acid is an asthmagen (Mlade et al., 2011), and inhalation or exposure to vapors can irritate the eyes, nose, throat, and lungs (Luttrell 2012). Pharyngitis and bronchitis with accompanying cough, shortness of breath and cough can result from chronic exposure to acetic acid (Luttrell, 2012). While not carcinogenic, acetic acid may be a cancer promotor due to hyperplasia (enlargement) of the mucosa in the esophagus prior to development of cancer

(Luttrell, 2012). Ernstgård et al. (2006) report mild nasal irritation at 10 ppm of acetic acid.

Benzene off-gasses from gasoline and diesel fuel as well as being a product of incomplete combustion. Benzene is a known human carcinogen (Category A), has a critical effect of decreasing lymphocyte counts, and is also associated with hematotoxic (related to the blood) effects in humans (U.S. EPA, 2003a). Benzene is known to the state of California to cause cancer and is a developmental toxin in males (CA OEHHA, 2015a).

Acetaldehyde occurs in fragrances (IFRA, 2011), tobacco smoke, other combustion sources, some food/beverages, and is exhaled in human breath (Rackes and Waring, 2016). Acetaldehyde is also formed in the atmosphere, from animal wastes, plant matter, fermentation, the breakdown of ethanol, etc. (U.S. National Library of Medicine, 2016a). Acetaldehyde is an asthmagen (Mlade et al., 2011), and is classified as “reasonably expected to be a human carcinogen” by the U.S. Department of Health and Human Services (U.S. DHHS, 2014), as a “probable human carcinogen” (Class B2) by the U.S. EPA (U.S. EPA, 1991) and as known to the state of California to cause cancer (CA OEHHA, 2015a). Acetaldehyde is also an irritant to the eyes, skin and respiratory tract (CA OEHHA, 2014b)

Benzaldehyde is used in fragrances (IFRA, 2011), essential oils from flowers fruits, leaves, etc., as a food additive and is released from combustion processes (National Library of Medicine, 2014a and references cited therein). Benzaldehyde and other carbonyls are formed by the reaction of ozone with many building products inside buildings (Poppendieck, et al., 2007 and Gall, et al., 2013). Benzaldehyde was reviewed by the international register of potentially toxic chemicals (IRPTC) in a screening information dataset (SID) produced under the OECD high production volume (HPV) chemicals programme (IPCS INCHEM, 1994 and references cited therein). It was sensitizing to 10% of the 100 human test subjects when applied to human skin using a patch test, was mutagenic in cell lines from both non-human animals (mice and Chinese hamsters) and human cells, caused lower body weight, neurological effects and death in non-human animals (rats) when fed benzaldehyde at 800 mg/kg of body weight (40% death in 16 days) to 1600 mg/kg of body weight (100% death in 2 days). Respiratory irritation occurred in non-human animals (rats) that inhaled 185 ppm of benzaldehyde for 2 weeks. Humans had a higher incidence of respiratory illness, and eye and skin irritation when workers were exposed to benzaldehyde at concentrations up to 5 mg/m^3. But this concentration is more than 500x higher than the $C_{ref,i}$ for benzaldehyde of 9 µg/m^3 and > 100x higher than the maximum concentration of benzaldehyde found in the database of 46 µg/m^3.

3.3.6 Disability Adjusted Life Years (DALYs)

Table 3.9 lists the 22 CoCs found in >5% of the SEs that have DALY damage factors from Huijbregts et al. (2005). The DALYs due to HCHO and the total of all other DALYs due to the other 21 compounds from the 296 SEs are described below. A limitation to this approach is that 92 compounds that occur in >5% of the SEs in the database lack any DALY parameters and are not considered further.

Table 3.11: Compounds in Database with damage factors (Huijbregts et al. (2005)

Compound	CAS #	∂D/∂I (y · kg^{-1}) Carc, lognormal	$k_{\partial D/\partial I}$ Carc, lognormal	∂D/∂I (y · kg-1) non-Carc., Inhalation lognormal	$k_{\partial D/\partial I}$ non-Carc., lognormal
Formaldehyde	50-00-0	0.76	26		
Styrene	100-42-5	3.30E-02	22	8.30E-03	96
Estragole	140-67-0	2.50E-02	23		
Napthalene	91-20-3	1.10E-02	24	6.10E-02	145
Acetaldehyde	75-07-0	6.40E-03	24	3.20E-02	215
Benzene	71-43-2	5.80E-03	24	3.10E-03	49
Limonene	5989-27-5	3.9E-03	26		
Benzaldehyde	100-52-7	1.30E-03	23		
1,4-Dichlorobenzene	106-46-7	1.20E-03	26	1.90E-03	126
Furfuraldehyde	98-01-1	1.10E-03	23		
2-Ethyl-Hexanol	104-76-7	7.70E-04	23		
Ethyl Benzene	100-41-4	2.20E-04	24	3.30E-04	126
Toluene	108-88-3	2.20E-04	23	4.70E-03	57
o, m, & p-Xylenes	1330-20-7	2.10E-04	23	7.20E-03	215
Ethyl Alcohol	64-17-5	7.90E-05	23		
1,2-Dichloroethane	107-06-2	0		5.00E+01	277
Methyl Isobutyl Ketone	108-10-1	0		1.40E-04	126
n-Hexane	110-54-3	0		7.70E-03	57
Cyclohexane	110-82-7	0		7.00E-04	66
Glycol Ether-EB	111-76-2	0		6.70E-03	128
Methyl Ethyl Ketone	78-93-3	0		2.60E-05	66
Cumene	98-82-8	0		6.50E-04	215

Lognormally distributed DALYs ($DALY_{mix,j,g}$) and standard deviations ($\sigma_{mix,j,g}$) were calculated for each of the 296 SE_j using equations 3.26 and 3.27 as developed in section 3.3.4. The median of the lognormal distribution of DALYs is reported. Where 68% and 95% confidence limits (CI) are shown, they are about the median.

Figure 3.12 shows a very strong correlation between HCHO and known DALYs in the database. HCHO clearly dominates the DALYs impact of the 22 known compounds with DALYs, even when C_{HCHO} is less than 7 ppb. Based on the mean of lognormal distributions, the average % of DALYs from formaldehyde in the 296 SEs is 98% (σ = 3%). As such, for the remainder of this analysis, I neglect the DALY contribution of the other 21 compounds and only evaluate the impact of DALYs due to HCHO.

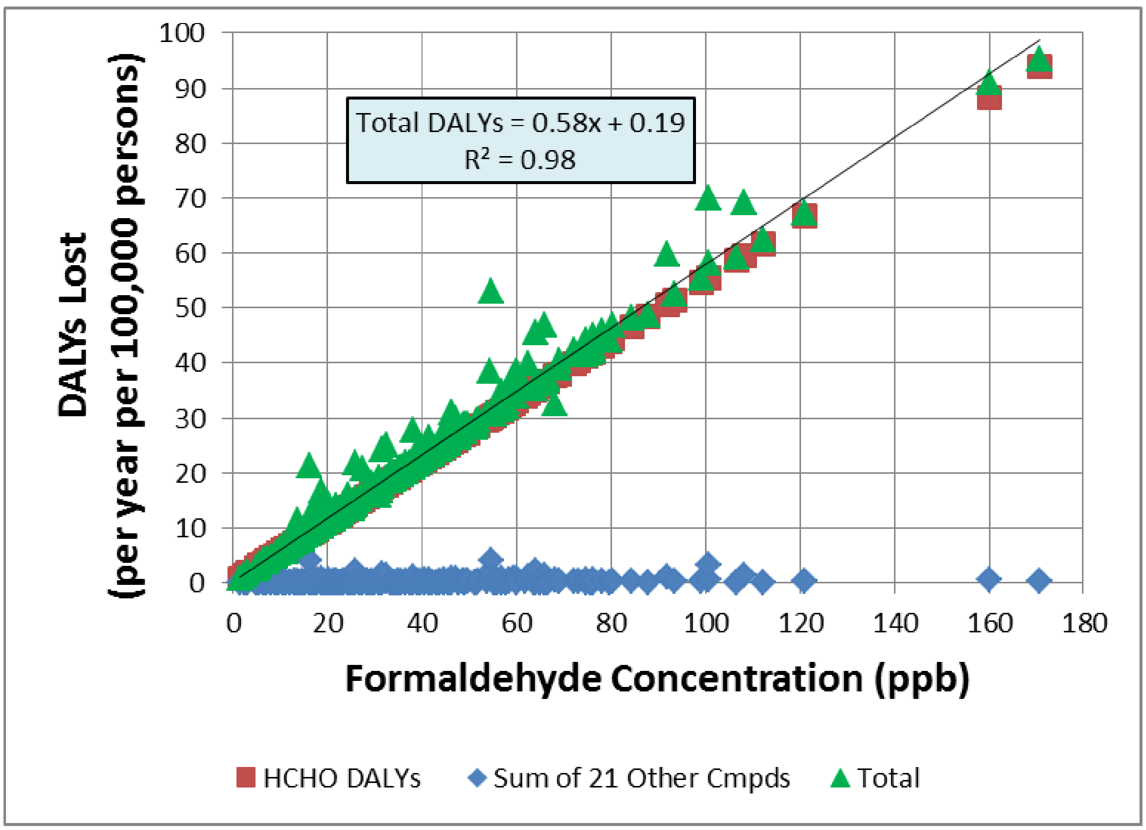


Figure 3.12: Correlation Between C_{HCHO} and DALYs in each SE

There is great uncertainty in the actual DALY value for HCHO. DALY uncertainty is explored by prescription of alternate metrics of the DALY distribution. Figure 3.13 shows the DALYs lost due to exposure to HCHO with 95% confidence intervals with the range of HCHO restricted to the RELs of interest (i.e. up to 81 ppb). At the upper bound of the 95% confidence interval, 1 DALY will be lost each year for every 100-people exposed to formaldehyde at concentrations of 29 ppb and above in residences.

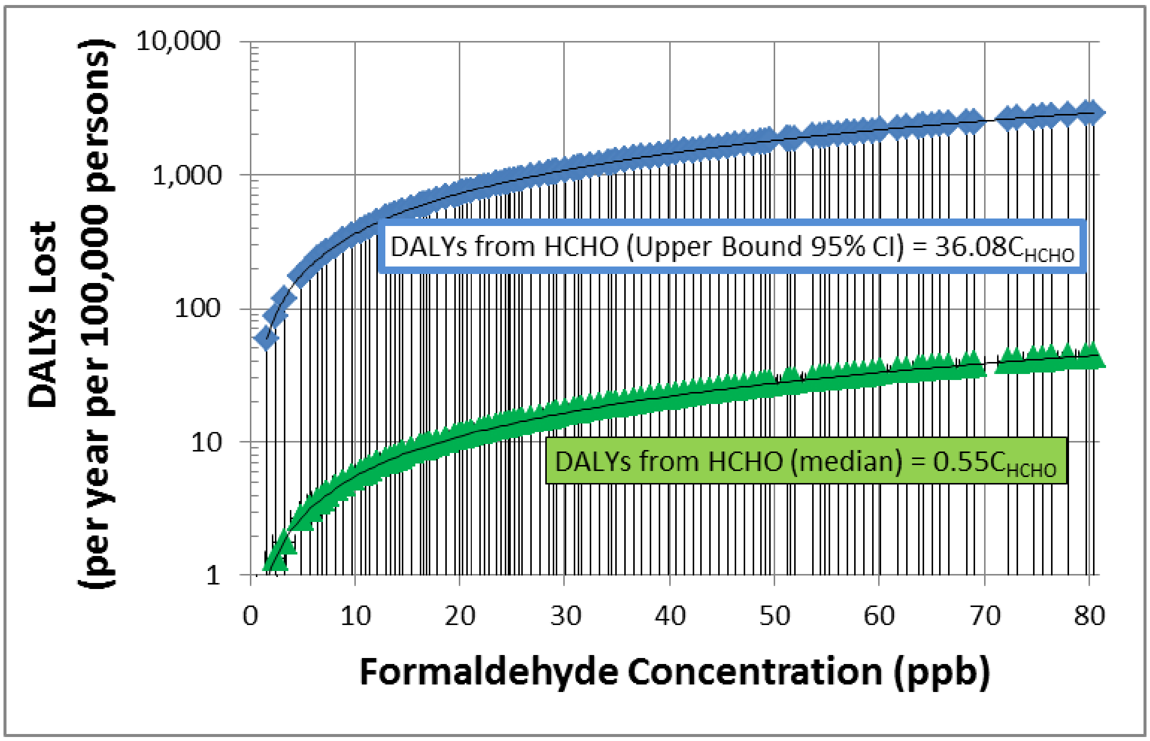


Figure 3.13: DALYs lost from only HCHO with 95% confidence intervals.

While the median value is always < 100 DALYs/100,000 person-years, at the 95% confidence interval, to achieve a level of <100 DALYs/100,000 person-year, C_{HCHO} < 4 ppb is required. This concentration is only 25% of the NIOSH reference level

(16 ppb) and is less than the CA OEHHA REL (7 ppb). This level of risk is a 1:1,000 risk of being personally impacted by a disability or death each year, or, over a 78 year life-time, a 1:13 chance (8%) of losing 1 year of life to disability or death based solely on exposure to formaldehyde in a residence. The risk increases to 1:33 at the upper bound of the 95% confidence interval at the WHO 81 ppb concentration, or over a 78 year life-time, a loss of 2.3 years of life to disability or death based solely on exposure to formaldehyde in a residence.

Figure 3.14 shows the same lognormal median DALY data shown in Figure 3.13 except with 68% confidence intervals.

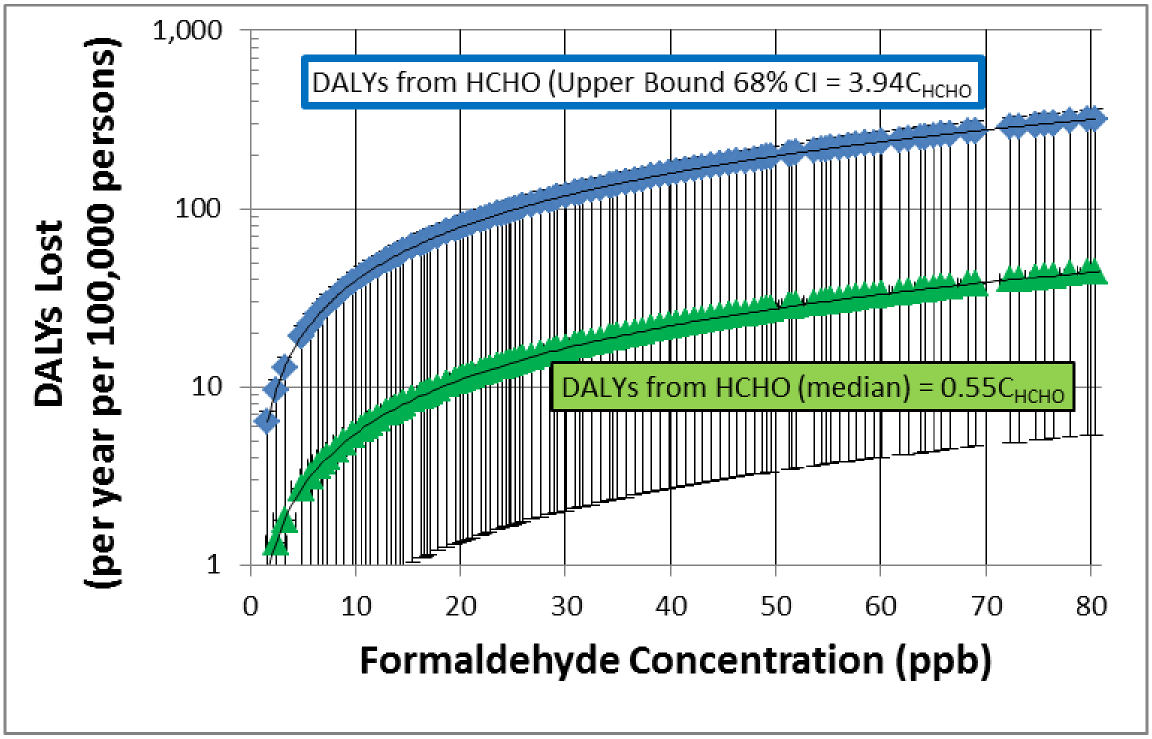


Figure 3.14: DALYs lost from only HCHO with 68% confidence intervals.

At the upper 68% confidence interval, to stay below 100 DALYs/100,000 person-years, C_{HCHO} must stay below 25 ppb or ~50% higher than the NIOSH REL of 16 ppb. To stay below 10 DALYs/100,000 person-years, at the 68% confidence interval, C_{HCHO} must stay below 2 ppb, which was only observed in one SE in the database.

Data presented in Figures 3.14 and 3.15 for the four RELs for HCHO are summarized in Table 3.10.

Table 3.12: DALYs lost annually from exposure to HCHO at home per 100,000 people for concentrations equal to specific RELs

Agency	CA OEHHA	FEMA/ NIOSH / CDC	Health Canada	WHO
REL →	7 ppb	16 ppb	40 ppb	81 ppb
	Annual DALYs lost per 100,000 people			
DALYs (Median)	4	9	22	45
Measure of DALY Uncertainty ↓				
68% Upper CI (84^{th} percentile)	31	72	180	360
95% Upper CI (97.5^{th} percentile)	260	590	1500	3000

An annual monetary cost can be attributed to the DALY risks shown inTable 3.10. The distribution of the value of a single DALY for an individual, DALY$, ranges from $0 to $690,000 as shown in Aldred et al. (2015). In this dissertation, $150,000/DALY (2014$) is used as a reasonable value as per Aldred et al. (2015). Table 3.11 provides the monetary value of DALYs lost annually per 100,000 people shown in Table 3/10 with a DALY valued at $150,000 (2014$). Values are shown in millions of dollars and assume 70% of the day is spent at home (16.8 h/day) for the range (7-81 ppb) of reference exposure limits for formaldehyde. The uncertainly of the DALYs provides a difference of a factor of ~65 between the median and the upper bound of the 95% confidence interval. For example, at 7 ppb, the median annual cost is $0.6 million per 100,000 people ($6/person-year) and the annual cost at the upper bond of the 95% confidence interval is $39.0 million per 100,000 people ($390/person-year).

Table 3.13: 2014$ Lost Annually due to HCHO in Homes per 100,000 People

Agency	CA OEHHA	FEMA/ NIOSH/ CDC	Health Canada	WHO
REL →	7 ppb	16 ppb	40 ppb	81 ppb
	2014$ in millions$ lost annually per 100,000 people			
2014$ lost (Median)	$0.6	$1.4	$3.3	$6.8
Measure of Uncertainty ↓				
68% Upper CI (84th percentile)	$4.7	$10.8	$27.0	$54.0
95% Upper CI (97.5th percentile)	$39.0	$88.5	$225.0	$450.0

* Uncertainly of DALYs only – uncertainly of $ value of a DALY not included.

On a population basis, annual monetary loss per person due to HCHO in a residence is obtained by dividing the values in Table 3.11 by 100,000 persons as shown in Table 3.12.

Table 3.14: 2014$ Lost Annually due to HCHO in Homes per Person

Agency	CA OEHHA	FEMA/ NIOSH/ CDC	Health Canada	WHO
REL	7 ppb	16 ppb	40 ppb	81 ppb
	2014$ lost annually per person			
2014$ lost (Median)	$6	$14	$33	$68
Measure of Uncertainty				
68% Upper CI (84th percentile)	$47	$108	$270	$540
95% Upper CI (97.5th percentile)	$390	$885	$2,250	$4,500

For a family of four, on a population basis, annual monetary loss due to HCHO in a residence is obtained by multiplying the values of Table 3.12 as shown in Table 3.12 by four as shown in Table 3.13.

Table 3.15: 2014$ Lost Annually due to HCHO in Homes for a Family of 4.

Agency	CA OEHHA	FEMA/ NIOSH/ CDC	Health Canada	WHO
REL	7 ppb	16 ppb	40 ppb	81 ppb
	2014$ per family of 4			
2014$ lost (Median)	$24	$56	$132	$272
Measure of Uncertainty				
68% Upper CI (84th percentile)	$188	$432	$1,080	$2,160
95% Upper CI (97.5th percentile)	$1,560	$3,540	$9,000	$18,000

Values from Table 3.13 can be used to evaluate the value of interventions to reduce C_{HCHO}. For instance, the annual monetary benefit of reducing the annual C_{HCHO} from 40 to 16 ppb at the median DALY value is $76 ($132-$56). However, at the upper bound of the 68% CI, the value is $648/yr and at the upper bound of the 95% CI the value is $5,480.

Table 3.14 shows the value per annual average ppb of HCHO in a home for a family of 4 in $2014/ppb.

Table 3.14: Value ($/ppb HCHO) of DALYs Lost Annually for a Family of 4

Measure of Uncertainty	2014$
Median 2014$ Value of DALYs lost annually due to HCHO in homes for a Family of 4/Ann. Avg. $C_{HCHO,i}$ ppb, ($/ppb HCHO)	$3
68% Upper CI 2014$ Value of DALYs lost annually due to HCHO in homes for a Family of 4/Ann. Avg. $C_{HCHO,i}$ ppb, ($/ppb HCHO)	$27
95% Upper CI 2014$ Value of DALYs lost annually due to HCHO in homes for a Family of 4/Ann. Avg. $C_{HCHO,i}$ ppb, ($/ppb HCHO)	$223

DALYs are reported in 2014$ in tables 3.10-3.14. Based on the consumer price index (CPI) (US Inflation Calculator, 2017), the difference between 2014$ and 2015$ is 0.1%. The difference between 2014$ and 2017$ is 2.6%. The difference in the value of $ between 2014 and 2017 is ignored in this study.

In Chapter 8, the DALYs lost per year per 100,000 persons for any C_{HCHO} between 0 and 81 ppb at different levels of risk (median, upper bound of 68% CI and upper bound of 95% CI) shown by the curve fits in Figure 3.13 and Figure 3.14 are reported. These values are used with Eqn. 3.30 to determine the monetized population averaged health value of mitigation strategies to reduce the C_{HCHO} calculated using ASHRAE Std. 62.2-2016 ventilation rates. The value of mitigation will be determined for any of the four RELs for HCHO shown in Table 3.13 that are lower than that obtained using ASHRAE Std. 62.2-2016 ventilation rates. The amount of money that can be invested in capital and maintenance cost that can be off-set by the population averaged health savings is dependent on the annual energy cost in the specific location as shown in (3.32) and reported in Chapter 8.

3.4 Summary

Formaldehyde (HCHO) is proposed as a primary metric for VOCs, including aldehydes, in residential applications. The database and analysis described in this study provide six key results that support this conclusion:

1. HCHO is ubiquitous – in 100% of SEs
2. HCHO is a significant contaminant of concern (CoC) in and of itself:
    a. 96% of SE Exceed C_{ref} based on CA OEHHA REL of 7 ppb
    b. 80% of SE Exceed C_{ref} base on NIOSH/CDC/FEMA REL of 16 ppb
    c. 41% of SE Exceed C_{ref} base on Health Canada REL of 40 ppb
    d. 4% of SE Exceed C_{ref} base on WHO REL of 81 ppb
3. C_{HCHO} is a good indicator of additional CoC in the same SE:
    a. If C_{HCHO} < 7 ppb, there is an 87% chance there are no other CoCs
    b. If C_{HCHO} < 16 ppb, there is a 63% chance there are no other CoCs

   c. If C_{HCHO} > 41 ppb, there is a 90% chance there are 1 or more other CoCs
   d. If C_{HCHO} > 81 ppb, there is a 100% chance there are 1 or more other CoCs
4. HCHO dominates the Hazard Index:
   a. 25% of the HI when the NIOSH REL of 16 ppb is used as $C_{ref,\ HCHO}$
   b. 42% of the HI when the CA OEHHA REL of 7 ppb is used as $C_{ref,\ HCHO}$
5. HCHO dominates (accounts for 98% of) the DALY impact of the 22 known compounds with DALYs.
6. Based on Spearman Correlation analysis, HCHO is statistically significantly correlated with 9 of the 10 CoC occurring in >5% of SE and the total VOCs, including aldehydes. The only CoC that is not correlated is camphor, which occurs in 10% of the SEs and exceeds its' C_{ref} in 7% of the SEs.

In order to monetize the risk from exposure to formaldehyde in residences to determine the financial value of reducing exposure to HCHO, a monetized value of the DALYs lost annually from exposure to HCHO in a home for a family of four were presented. In Chapter 8, the monetized benefit of reducing C_{HCHO} will be compared to the cost of energy required to provide what additional annual capital and maintenance costs can be justified for additional ventilation, gas phase filtration, and real-time formaldehyde monitoring equipment. In Chapter 9, the database is used to estimate the percent of where the HCHO monitor described in Chapter 9 would meet the OSHA accuracy requirements (± 25% of the true value) in spite of cross-sensitivities of the monitor to other contaminants.

Chapter 4 ield Data for Formaldehyde and Environmental Conditions

This chapter describes how field data for formaldehyde concentrations and environmental conditions were measured in two test houses (WC-2 and WC-3) at Oak Ridge National Laboratories under different ventilation and gas phase filtration (GPF) scenarios. Chapter 5 describes how the resulting field data were used to derive empirical correlations between indoor formaldehyde concentrations (C_{HCHO}), environmental conditions, and total air exchange rates (λ_{tot}). These correlations will be used in the model developed in Chapter 6 to determine annual energy use of these two test houses at ASHRAE Standard 62.2-2016 minimum ventilation rates and any additional ventilation required to achieve desired C_{HCHO} based on four reference exposure limits (RELs).

4.1 Test Homes

The two test houses used in this study are part of the Zero Energy Building Research Alliance (ZEBRAlliance) project, a federal and private-sector consortium that collaborated in building and evaluating experimental homes in Oak Ridge, TN. Four test homes were surveyed for VOCs, including aldehydes, and two homes (shown in Figure 4.1) were selected for more detailed interventions to study the impact of ventilation and gas phase filtration on IAQ parameters in these homes.

House WC-2 (Fig 4.1a) was selected as it uses Optimal Value Framing (OVF) with 2"x6" wood framing on 24-in centers, which is the design that can be most easily adopted by builders. House WC-2 (Figure 4.1a) was also found to be the house with the lowest air leakage when tested using the tracer gas technique when the outdoor intakes were sealed and all windows securely closed. House WC-3 (Figure 4.1b) was selected as it has the most innovative envelope system, which includes a phase change material (PCM). House WC-3 also had the highest formaldehyde concentrations of the set of homes. Consequently, at the end of the study, House WC-3 was equipped with a larger ERV than the other homes to provide additional ventilation to reduce C_{HCHO}. Hun et al. (2013a and b) provide detailed results of measurements made in these homes, including a regression analysis of C_{HCHO} and environmental factors, results of which were used in EnergyPlus modeling to provide monthly and annual average C_{HCHO} and energy used by the HVAC system.

a. Optimal Value Framing (OVF) House (House WC-2)

b. Phase Change Material (PCM) House (House WC-3)

Figure 4.1: ZEBRAlliance Test Houses (Miller et al. 2012).

4.2 Environmental Condition Measurements

This section describes measurement of environmental parameters, air exchange rates using the tracer gas decay method, and formaldeyde concentrations using active air sampling tubes and a commercially available real-time HCHO monitor.

4.2.1 Measurement of Indoor & Outdoor Environmental Conditions

As reported by Hun et al. (2013a), all indoor environmental conditions were reported every 15 minutes and outdoor conditions were reported every minute. Data were collected on two existing ORNL micro-loggers and dedicated desktop personal computers (PCs) in each house (Miller et al. 2010). Data which were automatically uploaded to the ORNL server nightly were used.

The following parameters were considered: indoor and outdoor temperature (T_{in} and T_{out}), indoor and outdoor %RH ($\%RH_{in}$ and $\%RH_{out}$), and interior oriented strand board (OSB) temperatures in the northeast (NE), and southwest (SW) roofs ($T_{NE\ roof\ OSB\ int}$, $T_{SW\ roof\ OSB\ int}$) and interior OSB temperatures in the south (S), north (N), east (E), and west (W) facing walls ($T_{S\ wall\ OSB}$, $T_{N\ wall\ OSB}$, $T_{E\ wall\ OSB}$, $T_{W\ wall\ OSB}$).

Honeywell 192-103LET-A01 and Honeywell HIH-4000 sensors were used to monitor indoor temperature (+/- 0.2 ^{o}C) and relative humidity (±5 %RH below 60%RH and ±8 %RH from 60-100 %RH), respectively. A Campbell CS215 sensor was used to monitor outdoor temperature (+/- 0.4 ^oC from 5 to 40 ^oC) and relative humidity (±2% from 10 to 90 %RH).

On-site solar insolation, wind and outdoor temperature measurements were used to calibrate the EnergyPlus™ models for infiltration in the ZEBRAlliance homes (Hun et al. 2013a). EnergyPlus™ used the infiltration by flow coefficient model which is called the "enhanced" or "AIM-2" model and is based on the work of (I. Walker & Wilson, 1998). The same calibrated models were used in this work. To model the energy used at the ZEBRAlliance site, Hun et al. (2013a) used on-site environmental data for purposes of computer modeling. To provide more generic results and clearly differentiate this follow-on work from the work reported by Hun et al. (2013a), energy use in this dissertation is based on typical meteorological year (TMY3) data from the Knoxville airport and seven additional sites across the country for which appropriate environmental data were available as input to models. For this dissertation, site locations for the two ZEBRAlliance homes were assumed to be at the same location as the TMY3 data is reported.

4.2.2 Measurement of Whole House Air Exchange Rates

Whole house air exchange rates (λ_{tot}) were measured based on the concentration decay method specified in ASTM Standard E 741-00 (reapproved 2006) (ASTM, 2006). Figure 4.2 shows a typical set-up of the tracer gas sampling equipment.

Figure 4.2: Tracer gas test equipment

A tracer gas (R134a or SF_6), an INNOVA Air Tech Instruments 1303 Multipoint Sampler and Doser, and an INNOVA AirTech Instruments 1412 Photoacoustic Field Gas Monitor were used to collect data used in calculating AERs for this dissertation. The detailed λ_{tot} protocol and λ_{tot} Field Test Data Sheet are presented in Appendix C.

Using the tracer gas concentrations collected with the INNOVA equipment, the λ_{tot} were calculated using a detailed protocol for data analysis, including uncertainty analysis of the ventilation rate measurements based on ASTM Standard E 741-00 (ASTM, 2006). Details of the λ_{tot} data analysis are shown in Appendix D.

Tracer gas decay from both floors were combined. Baseline measurements were made with outdoor air intakes capped off and ventilation systems turned off. Whole house AERs ranged from a very low rate of 0.0170 h^{-1} ± 0.0006 (±3.5%) in House WC-2 with no outdoor air ventilation to a maximum of 0.481 h^{-1} ± 0.036 (±7.5%) in House WC-3 with the maximum supply ventilation used in this study. As reported in Hun et al. (2013a), the average confidence limit on AER based on 56 samples taken in the summer of 2012 was +/- 1.4%.

4.2.3 Summary of Environmental Conditions

A summary of indoor and outdoor environmental conditions measured during this study are summarized in Table 4.1.

Table 4.1: Indoor and Outdoor Environmental Conditions

Parameter	WC-2	WC-3
Outdoor Temperature, T_o	3.1 - 34.1 ^oC	12.5 – 34.1 ^oC
Outdoor Relative Humidity, $\%RH_o$	17 - 100%	38 - 100%
Indoor Temperature, T_i	22.8 - 27.5 ^oC	21.7 - 23.6 ^oC
Indoor Relative Humidity, $\%RH_i$	31 - 65%	41 - 61%

4.3 Formaldehyde Measurements

This section describes measurement of formaldehyde using air sampling tubes and a commercially available real-time HCHO monitor.

4.3.1 Measurement of C_{HCHO} Using DNPH Tubes

Formaldehyde was sampled and analyzed based on EPA TO-11a using dinitrophenyl hydrazine (DNPH) tubes for 1, 2 or 24 hour average C_{HCHO} in the test houses (U.S. EPA, 1999). The HCHO sampling protocol used in the field is provided in Appendix E. The majority of HCHO analysis was performed by the author at Matrix Analytical Labs based on EPA Standard TO-11a. Figure 4.3 shows a typical HCHO sampling location in a test house using a DNPH tube.

Figure 4.3: Formaldehyde air sampling

A detailed uncertainty analysis of the C_{HCHO} measurements, including the method used to calculate the uncertainty of each individual C_{HCHO} measurement is provided in Appendix F. Data validation and uncertainty analysis rely on methods described in ASHRAE Guideline 2-2010 (ASHRAE, 2010a), including the use of Chauvenet's Criteria for rejecting outliers. Two approaches to calculate uncertainty were used: error propagation analysis and duplicate field samples.

The greatest uncertainty is in the measurement of the mass of formaldehyde. The TO-11a test method (U.S. EPA, 1999) was selected to sample and analyze the air samples for HCHO as it was understood to be the "gold standard". After the field work and laboratory analysis were complete, it was discovered that the single pass (SP) DNPH derivative extraction method specified in the TO-11a method does not extract all of the derivatized DNPH by a factor of 1.8 as described below. In the laboratory, the SP extraction method passes 5.0 mL of acetonitrile (MeCN) directly through the sampling tube that air was collected in during the field sampling. A more complete DNPH derivative extraction method used by Matrix Labs as recommended by Supelco (referred to in this study as the "Shake-a-Vial" or SV extraction method) places all of the DNPH from the sampling tube in a 7 mL glass vial, adds 5.0 mL of MeCN and shakes the vial on an automated shaker for 30 minutes. An extraction procedure correction factor (f_{ext}) of 1.8 ± 0.2 was determined by taking the ratio of the DNPH derivative extracted from one sample with the SV method and the DNPH derivative extracted from the matching sample with the SP extraction method. Nine duplicate field samples were used to determine the correction factor. This approach accounts for not only the uncertainty in the extraction method, but also all other uncertainties in the field, and associated with sample transport and storage.

Error propagation analysis is dominated by the fractional uncertainty of the extraction procedure correction factor ($u_{f_{ext}}$), as shown below:

$$\pm 1\ \sigma,\ 68.3\%;\ u_{fext,68\%} = \pm 0.12 * C_{HCHO}$$

$$\pm 1.96\ \sigma,\ 95\%;\ u_{fext,95\%} = \pm 0.24 * C_{HCHO}$$

Eleven pairs of duplicate 24 hour field samples, taken during a single sampling session, were analyzed using the single pass extraction procedure to obtain a fractional uncertainty of the C_{HCHO} measurements ($u_{C_{HCHO}}$). This means that the C_{HCHO} is known within $\pm\ u_{C_{HCHO}} * C_{HCHO}$. After applying Chauvenet's criteria to exclude outliers, ten duplicate pairs remained. The average overall fractional uncertainty associated with measuring the C_{HCHO} in these ten pairs of field duplicates is shown below at 68% ($u_{C_{HCHO},68\%}$) and 95% confidence levels:

$$\pm 1\ \sigma,\ 68\ \%;\ u_{C_{HCHO},68\%} = \pm 0.14 * C_{HCHO}$$

$$\pm 1.96\ \sigma,\ 95\%;\ u_{C_{HCHO},95\%} = \pm 0.28 * C_{HCHO}$$

Throughout the rest of this study, the uncertainty of the concentration of formaldehyde (C_{HCHO}) is reported using $u_{C_{HCHO},68\%} = \pm$ 14% C_{HCHO}. Data for duplicates used to determine these uncertainties are provided in Appendix F.

4.3.2 Measurement of C_{HCHO} Using a Real-Time HCHO Monitor

A secondary measurement technique for continuously monitoring formaldehyde for 2-3 weeks with a time resolution of 30 minutes was used in this study. This commercially obtained coupled sensor-spectrophotometric device (CSSD) (Shinyei Technology Co., Ltd., 2011) is based on a chemical sensor element in which HCHO reacts with β-diketone and ammonia with spectrophotometric analysis of the extent of that reaction (Maruo et al. 2008a, 2008b, 2009, 2010, Maruo & Nakamura, 2011). The supplier provided alternate software that allowed output of C_{HCHO} measurements below the 20 ppb level provided in their standard software.

The author of this dissertation teamed with Dr. Ellison Carter, then a Ph.D. candidate at the University of Texas at Austin, to calibrate the Shinyei units. A KinTek 491MM standard gas generator (Kin-Tek, LaMarque, TX, USA; model 491MB) and permeation tube oven on loan from NIST was used to provide a known

C_{HCHO} as shown in Figure 4.4 and Figure 4.5.

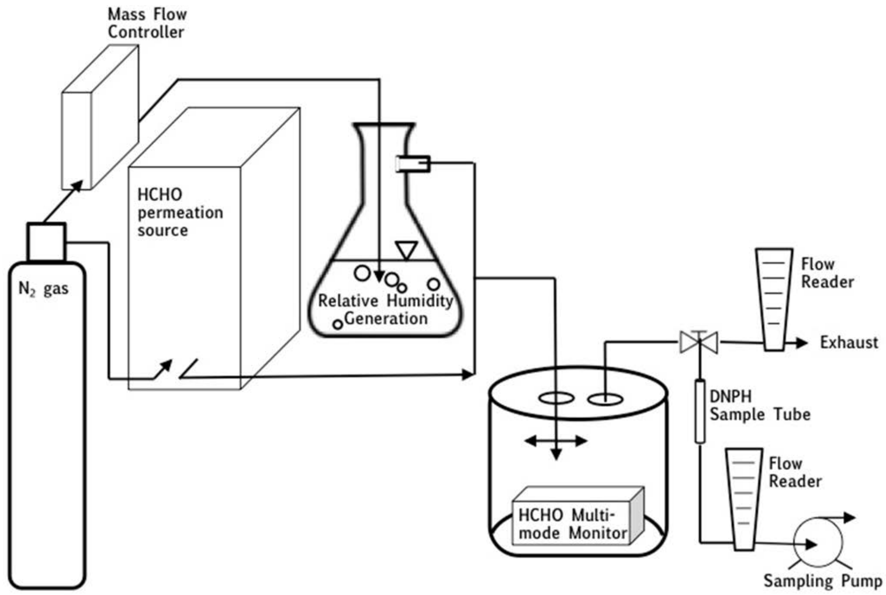


Figure from (Carter, et al. 2013)
Figure 4.4: Experimental Set-up for Calibration of Shinyei HCHO Meters

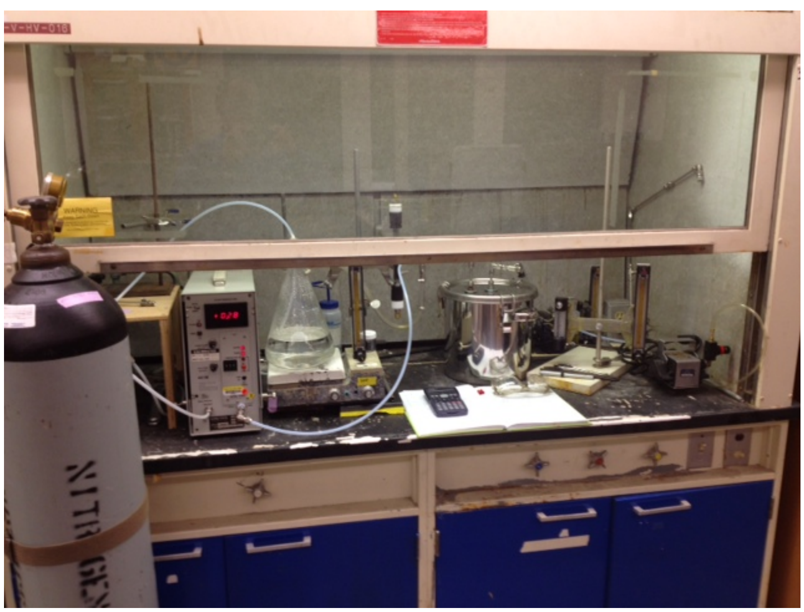


Figure 4.5: Laboratory Test Set-up for Calibration of Shinyei HCHO Meters.

Results of laboratory calibration of the four monitors (#12, 35, 37 and 40) used in this study showed a linear response from 5-50 ppb with a coefficient of determination of >0.99 between the Shinyei monitors and the TO-11a DNPH method (using the SV extraction method discussed in section 4.3.3) as shown in Figure 4.6.

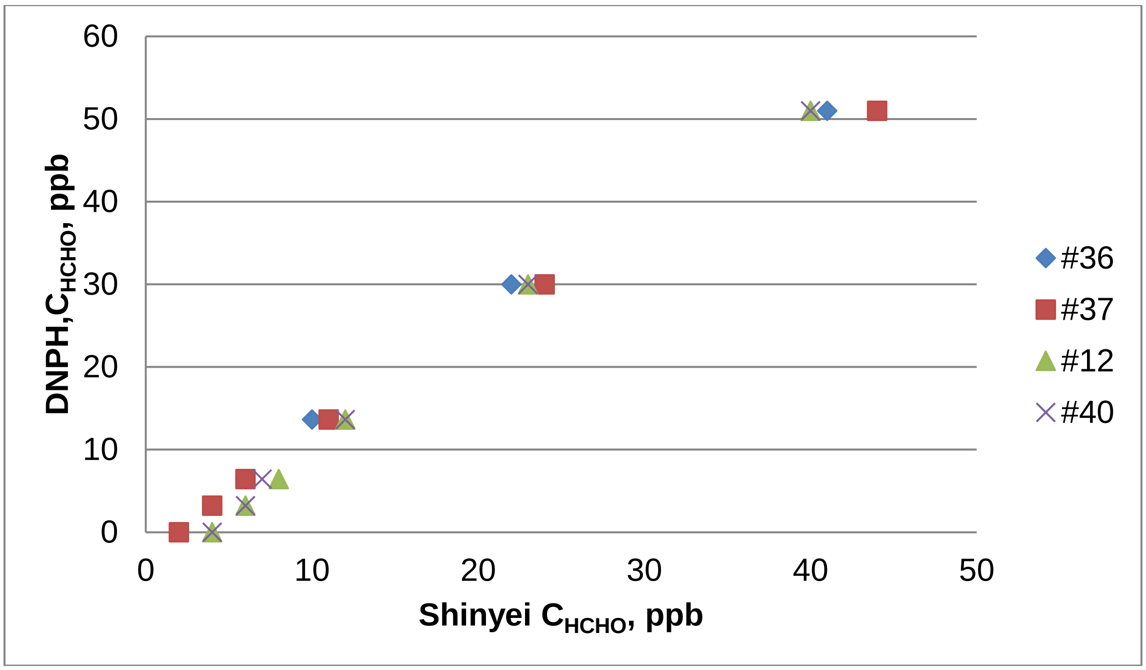


Figure 4.6: C_{HCHO} from Shinyei Monitors and DNPH Samples

A minimum detection limit (MDL) of 2 ppb in a laboratory setting for the CSSD was found as reported by Carter et al. (2013). A pre-publication draft of this paper is presented in Appendix G.

Two of the Shinyei monitors calibrated in the work described above were used at Oak Ridge National Laboratories by the author to collect quasi-real-time (30 minute samples) measurements of formaldehyde, which were reported by Hun et al., (2013a, 2013b; Hun, 2014).

Data obtained from the Shinyei monitors by the author in a second set of ORNL homes where intermittent ventilation was studied were not reported by Hun & Jackson (2014) due to concerns about inaccurate readings. Co-located Shinyei monitors were tested twice in an unoccupied test house as shown in Figure 4.7. New sensors from the same lot of sensors were used for each monitor for each co-located test.

Figure 4.7: Co-located Shinyei Monitors in Un-occupied ORNL test House

The 1st colocation test results are shown in Figure 4.8. The average difference between the two co-located monitors was 29% (s.d. ±7%).

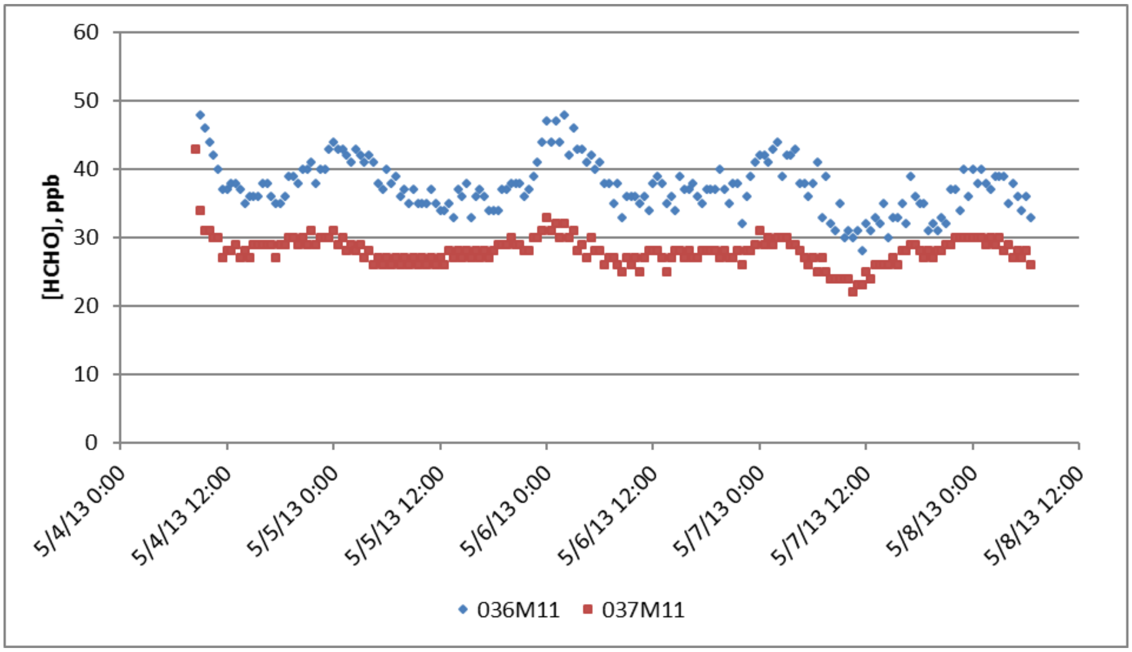


Figure 4.8: 1st Co-location Test of Shinyei HCHO Monitors

The results from the 2nd colocation test, in the exact same location with new sensors from the same lot as the 1st colocation test, are shown in Figure 4.9. The average difference between the two co-located monitors was a more acceptable 5% (s.d. ±10%).

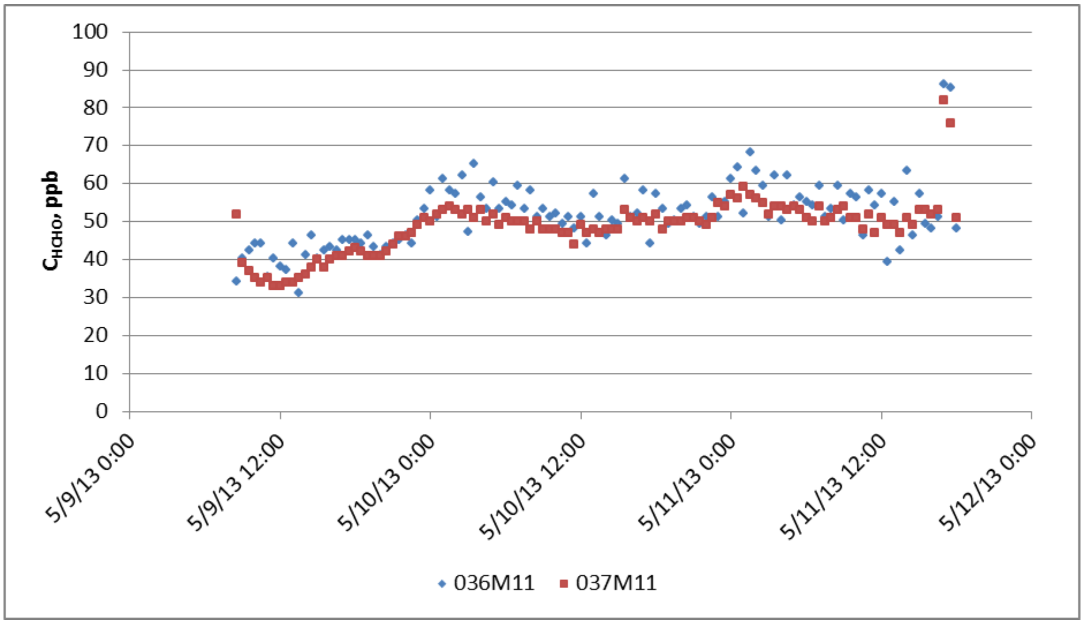


Figure 4.9: 2nd Co-location Test of Shinyei HCHO Monitors

The differences between the results of the two co-located tests are unexplained. One concern is potential thermal excursions above the 30 °C storage temperature during shipment of the sensors in the summer, or in automobile transport on hot days. The sensors are shipped in uninsulated and non-temperature controlled packaging by international currier service. This concern could be tested by subjecting several sensors to elevated temperatures (i.e. 40-50 °C) for 2-3 days and comparing the performance of those sensors to control sensors that had not experienced such a thermal excursion. Full exploration of this potential source of variation requires monitoring the sensor from fabrication at the supplier in Japan, through international transit, storage once the sensors have arrived and local transport to the field site.

While a full exploration of this potential source of variation is beyond the scope of the current project, the co-location data, additional data and possible methods to explore and resolve the potential temperature excursion issues was provided to the manufacturer. Despite numerous discussions with the manufacturer and distributor, no resolution of this issue has been found. It is recommended that prior to use of these or similar HCHO monitors that use thermally sensitive components, the thermal history of sensors be carefully tracked and controlled to avoid exposure to temperatures above or below manufacturer recommendations. An alternate precaution is to avoid shipping sensors except in the winter – this is of particular concern in locations (such as Texas) that routinely experience outdoor temperatures in excess of 40 ^{o}C. Additionally, a two-point calibration in the laboratory (i.e. 0 and 81 ppb) of each sensor/monitor to be used in the field with careful control of temperature in transport to the field may provide more accurate results. Note that calibration of individual sensors prior to use in the field was not done in this study.

Nirlo et al. (2015) found that the Shinyei monitors were strongly correlated with DNPH tube samples for formaldehyde at 16 ppb, but not at 7 ppb.

4.4 Formaldehyde Concentrations in Test Homes

Baseline 24-h VOC, including aldehyde, measurements were taken in House WC-3 in August 2011 and in Houses WC-2 and WC-3 in November 2011 as reported by Hun et al. (2013a&b). See section 3 in Appendix G. Field work for this project was conducted in Oak Ridge, TN in the two site-built, unoccupied, energy efficient single family test homes described in this dissertation between August 2011 and February 2013. Table 4.2 shows a list of all interventions conducted in the field.

Table 4.2: Field Test Schedule

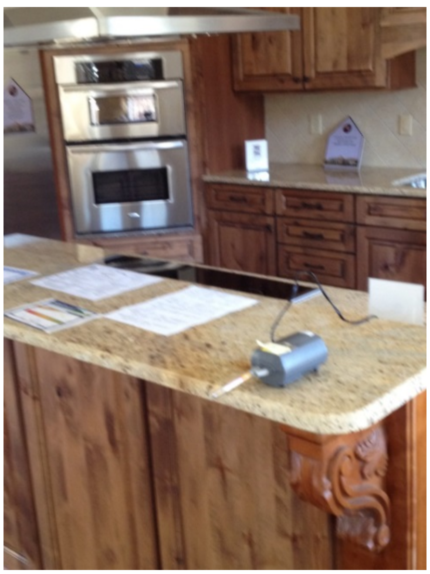
Test	Dates	House WC-2	House WC-3
1 (Pilot)	11/21/11 – 11/28/11	-	T1-GF-H3: Gas-phase filtration
2 (Pilot)	3/11/12 – 3/21/12	-	T2-GF-H3: Gas-phase filtration
3	7/19/12 – 7/27/12	T3-SV-H2: Supply ventilation	T3-SV-H3: Supply ventilation
4	8/9/12 – 8/17/12	T4-SV-H2: Supply ventilation	T4-SV-H3: Supply ventilation
5	8/16/12 – 8/24/12	T5-EV-H2: Exhaust ventilation	-
6	9/28/12 – 10/6/12	T6-EV-H2: Exhaust ventilation	T6-EV-H3: Exhaust ventilation
7	10/3/12 – 10/11/12	T7-GF-H2: Gas-phase filtration	T7-GF-H3: Gas-phase filtration

Abbreviations: T, test, EV, exhaust ventilation; GF, gas-phase filtration; H, house; SV, supply ventilation.
Table modified from Hun et al. 2013a

4.4.1 Seasonal HCHO Samples

Air samples were taken to measure C_{HCHO} from the counter-top in the open kitchen/dining/living area of each house using DNPH tubes as described in section

4.3.3. A Shinyei HCHO monitor was used as a secondary measurement of C_{HCHO}. Representative locations in the combined kitchen/dining room area are shown in Figure 4.10a for DNPH sampling and in Figure 4.10b for the Shinyei HCHO monitor. The DNPH samples were collected with modified aquarium pumps provided by Matrix on the granite countertop with the DNPH tube hanging over the edge of the countertop.



a: DNPH sampling

b: Shinyei HCHO Monitor

Figure 4.10: Typical Formaldehyde Sampling Locations

To characterize seasonal variation in HCHO in these homes, air from the kitchen/dining room was sampled using DNPH tubes as shown for houses WC-2 and WC-3 in at least four seasons as shown in Figure 4.11.

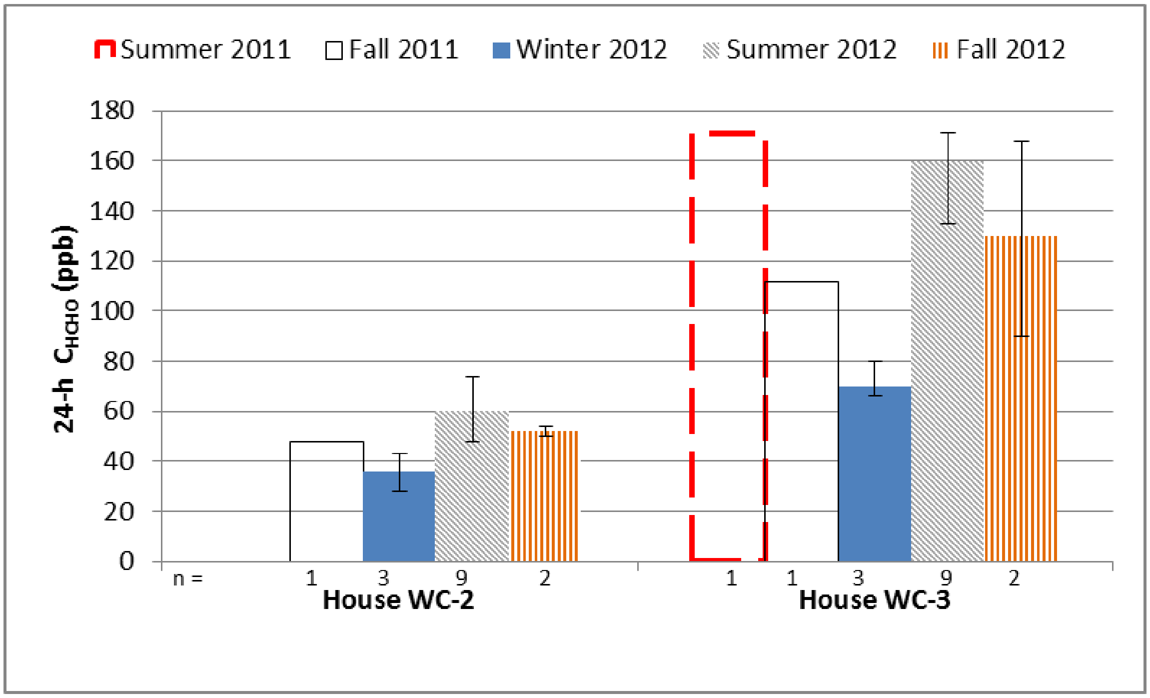


Figure 4.11: Seasonal C_{HCHO} from two Test Houses.

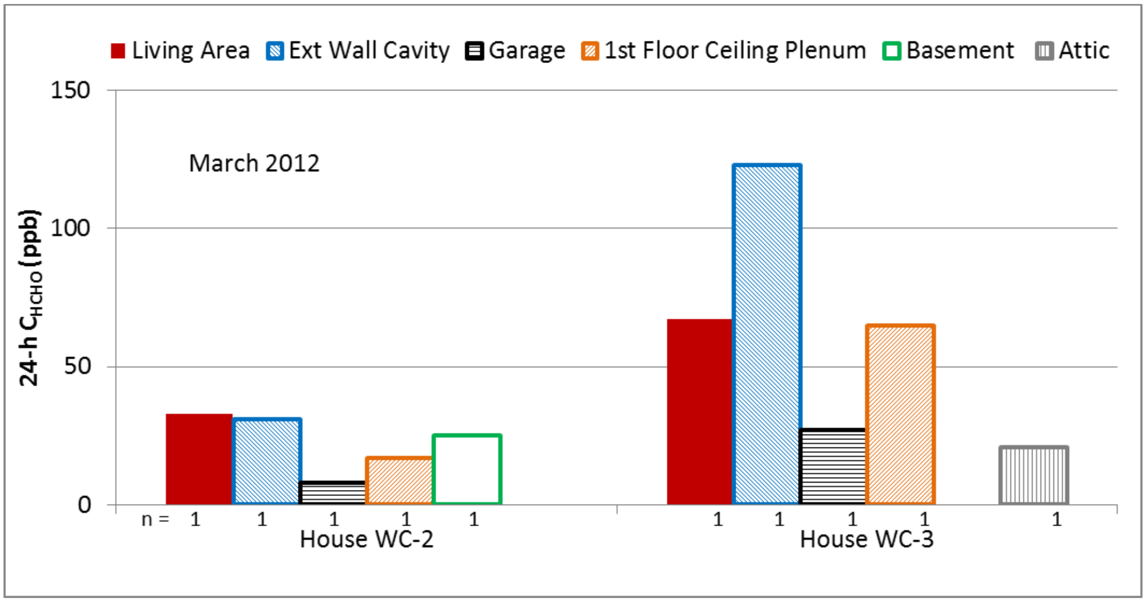
a. Measurements are from 24-hr air samples.
b. Whiskers indicate minimum and maximum measured values of n samples taken.
c. Mechanical ventilation rates ~30 cfm (House WC-2 = 0.04 h^{-1}, House WC-3 = 0.06 h^{-1}) when the 2011 and winter 2012 data were collected. Mechanical ventilation was shut down during the collection of the summer and fall 2012 data.

4.4.2 Characterization of Sources of HCHO

To characterize sources of HCHO in the houses, air samples were collected from the wall cavities, between the 1st and 2nd floor, the attic, crawlspace, and the garage as shown in Figure 4.12.

Air samples were collected for 24 hours through DNPH tubes using modified aquarium pumps with a flow rate of ~200 mL/min, which was measured using a positive displacement calibrator (Bios Defender 530 DryCal) with NIST traceable calibration at the beginning and end of the sampling period. Samples from open rooms were drawn directly into the DNPH tube. For wall and interstitial space samples, ¼" rubber and copper tubing were used to penetrate walls at electrical outlets and access the interstitial space between floors through a hole drilled in a supply air vent boot. The detailed DNPH tube sampling protocol for the source analysis is provided as Appendix C.

This characterization shows that the walls/building envelope may be a significant source of HCHO, assuming sufficient air exchange with the interior space. The attic, garage, and crawlspaces were not significant sources when measured. The C_{HCHO} in the exterior wall cavity in House WC-3 is much higher than the C_{HCHO} in the living area. This is not surprising as the OSB, engineered composite studs, and PCM used in the walls of House WC-3, all have HCHO in them. Of the ORNL test houses studied in the work reported by Hun et al. (2013a), House WC-2 is the most likely to be adopted by builders and House WC-3 had the highest C_{HCHO} (i.e. a "worst case"). These two houses were selected for detailed modeling in this dissertation.



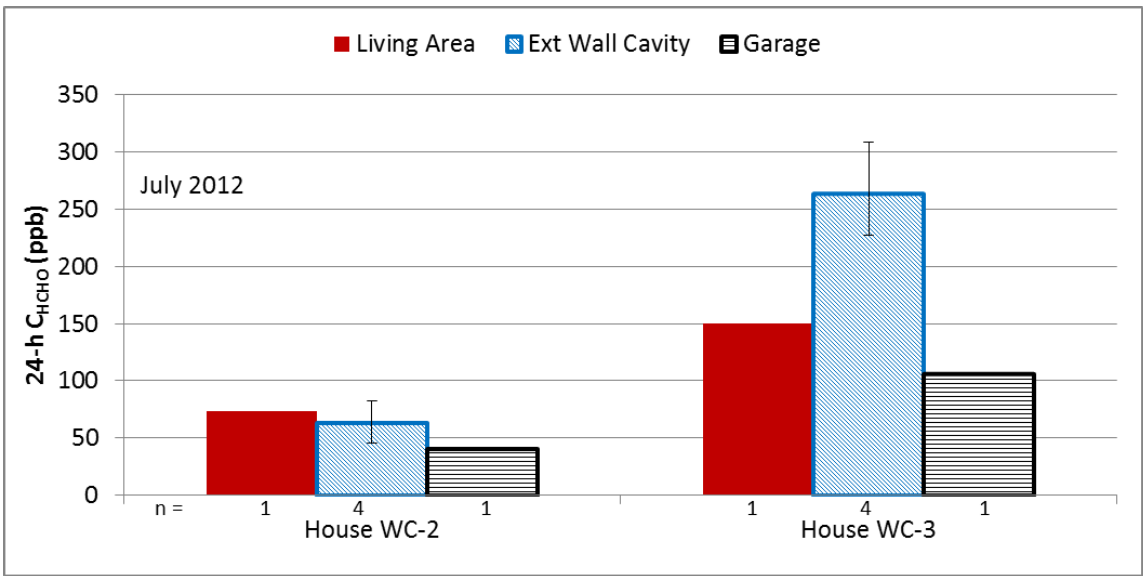


Figure 4.12: C_{HCHO} in March/July 2012 Within and Adjacent to the Living Area

a. Measurements are from 24-hr air samples.
b. Whiskers indicate minimum and maximum measured values of n samples taken.
c. Ventilation rates were less than 0.15 h^{-1} when these measurements were gathered.

4.4.3 Interventions with Ventilation

ASHRAE 62.2-2010 (ASHRAE, 2010a) minimum required mechanical ventilation rates (~0.1 ACH) as well as higher ventilation rates up to a maximum of 0.48 ACH were tested. Both supply (+ pressurization) and to a lesser extent exhaust (- pressurization) were tested.

All mechanical ventilation was supplied through a window using a blower housing as shown in Figure 4.13 with a HEPA filter and 1.55 kg of a proprietary carbon optimized for removal of formaldehyde (Amaircare model AWW675).

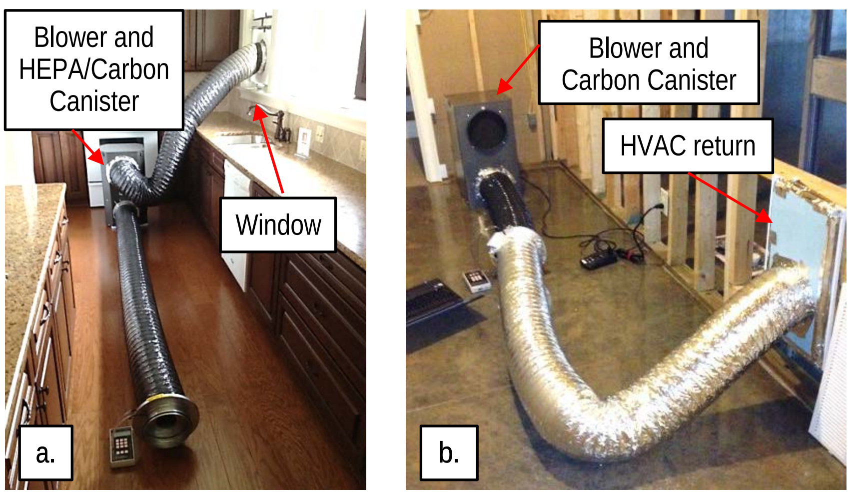


Figure 4.13: Mechanical Ventilation and Gas-Phase Filtration Installation.
a. Supply and exhaust ventilation provided with a blower attached to a window.
b. Air was treated by moving it through a blower with a filtration canister; the treated air was then supplied to the rest of the house through an existing HVAC return (Hun et al.2013a).

Whole-house λ_{tot} were measured during all interventions using the tracer gas approach described in Section 4.3.2.

A significant result is that supply ventilation provided far greater reduction of C_{HCHO} than exhaust ventilation as shown in Figure 4.14. For one case (case 4 in Figure 4.14), increasing total exhaust ventilation by a factor of 16 resulted in an increase in C_{HCHO}. The type of ventilation (supply or exhaust) is the dominate factor on the impact that ventilation has on C_{HCHO}. This suggests that much of the formaldehyde originates from sources in the building envelope, through which air travels under exhaust ventilation. Importantly, the results described here are for unfurnished and un-occupied houses (with simulated occupany by providing thermal loads and running appliances and showers on a schedule).

For the results shown in Figure 4.14, the percent reduction in C_{HCHO} attributable to the reduction of temperature is shown by the shaded bars. For supply ventilation, the impact of reduced temperature had only a small effect on C_{HCHO} reduction. This was not the case for exhaust ventilation during which temperature reductions played a more significant role.

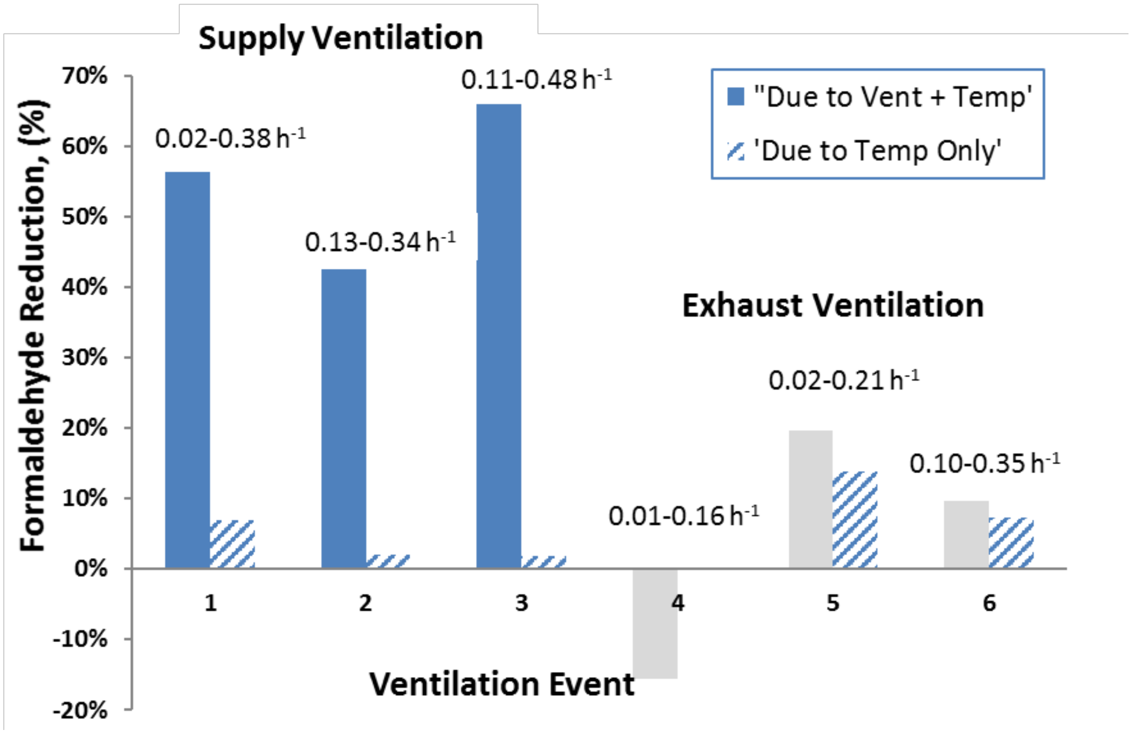


Figure 4.14: Supply/Exhaust Ventilation Impact on Formaldehyde Reduction.

4.5 Summary

This chapter is a part of Phase 2 of the dissertation dealing with energy as shown in Figure 1.1. This chapter describes how field data were collected, interventions that were made and the validity of test equipment used in the study.

Key findings include:

- C_{HCHO} is higher in the summer than winter, although the difference in more pronounced in house WC-3.
- The Shinyei HCHO monitor provides greater temporal resolution than the DNPH air sampling.

- Careful thermal control of Shinyei HCHO sensor tabs is important.
- Independent of thermal effects, supply ventilation, in the two target homes was much more effective in reducing C_{HCHO}.
- The efficacy of supply vs. exhaust ventilation suggests that a significant source of HCHO in these homes is the building materials used in the walls.
- The observation may not be as pronounced in furnished and occupied homes where additional sources of HCHO are inside the home rather than primarily in the wall cavities.

Chapter 5 continues Phase 2 of the dissertation and describes the development of the empirical model for C_{HCHO} more fully defined by (D.E. Hun et al., 2013a), which is attached as Appendix A of this dissertation. The empirical models described in Chapter 5 form the basis of the rest of the energy modeling and results described in Chapters 6 – 8.

Chapter 5 Empirical Model for C_{HCHO} in Unoccupied House

This chapter describes how the field data presented in Chapter 4 were used to develop empirical correlations between environmental factors, AER and C_{HCHO}. These correlations are the key to determining energy required to achieve specific C_{HCHO} RELs as described in Chapters 6 - 8.

It is understood and acknowledged that the results for these two homes would have significant uncertainty if applied to other house designs or occupied homes. The key experimental data used in this analysis is the correlation developed by the author for C_{HCHO} versus indoor temperature (T_{in}) and air exchange rate (λ_{tot}) for the two un-occupied ORNL test homes as shown in Section 5.1. The approach used in this study can be more broadly applied, only if the correlation between C_{HCHO}, T_{in} and λ_{tot} , and how λ_{tot} changes throughout the year, are known for any house design. This study involves estimates of the additional energy, above that required to meet the minimum ventilation requirements of ASHRHAE 62.2-2016 (ASHRAE, 2016), required to achieve specific (7, 16, 40 and 81 ppb) REL C_{HCHO} by using additional ventilation or gas phase filtration (GPF).

The work reported by Hun et al. (2013a, 2013b, and 2014), all of which the author of this dissertation is a co-author on, used ASHRAE 62.2-2010 ventilation rates as their base case. Monthly average C_{HCHO} and projected energy use for various ventilation rates and amounts of gas phase filtration (GPF) were reported. No attempt was made to determine optimal energy use to achieve specific C_{HCHO} RELs, which is the objective of the current study.

5.1 *Correlation between C_{HCHO} and Environmental Factors*

MATLAB® 2012R was used to explore the correlation of C_{HCHO}, indoor and outdoor temperature in K (T_{in}; T_{out}), indoor and outdoor relative humidity (RH_{in}; RH_{out}), and total air exchange rate (λ_{tot}). Twenty-four-hour average environmental data were used. Air exchange rate measured on the same day were assumed to be constant for the entire 24-hour period even though the sampling period for the λ_{tot} was less than 24-hours. It is acknowledged that this assumption is not completely valid as infiltration does change with windspeed and temperature differential which vary over the day. This assumption is more valid for house WC-2 (ACH50~1.2) vs. house WC-3 (ACH50~3.6). House WC-2 had 17 data sets and House WC-3 had 15 data sets. Only supply ventilation (+ pressurization), or natural infiltration (without mechanical ventilation) data were used due to the impact of exhaust ventilation described in section 4.4.3.

Correlations derived with MATLAB® as reported by Hun et al. (2013a, 2013b, and 2014) are shown in Eqn. 5.1 and Eqn. 5.2. No emission rate effect such as that described by Hult et al.(2015) was observed or accounted for in this dissertation.

These houses were unfurnished and unoccupied. As described by Hun et al most of the HCHO was coming from the wall cavity such that back-pressure phenomena due to internal soures of formaldeyde were not observed. Key sources of formaldehyde in these homes are the buiding materials, including oriented strand board (OSB), engineered structural wood, and, in house WC-3, formaldehyde is a component of the phase change material (PSM) used in the walls. These correlations are only valid for the houses studied, and then only for the time period they were measured in (i.e. not after additional off-gassing occurred during the following years).

$$C_{HCHO,\ WC\text{-}2} = -90.4\ \lambda_{tot} + 9.43\ T_{in} - 2747\ ;\ R^2 = 0.82;\ RE = 14.6\% \qquad (5.1)$$

$$C_{HCHO,\ WC\text{-}3} = -270\ \lambda_{tot} + 32.85\ T_{in} - 9556\ ;\ R^2 = 0.93;\ RE = 8.3\% \qquad (5.2)$$

where

n = house number (2 or 3)

$C_{HCHO,\ WC\text{-}n}$ = concentration of formaldehyde in house n, ppb

λ_{tot} = total air exchange rate including both infiltration and mechanical ventilation, h^{-1}

T_{in} = indoor temperature, K

Limitations of the correlations shown in Eqn. (5.1) and Eqn. (5.2 include:

- Steady-state conditions are assumed for the entire 24-hour period. These same equations are used for hourly modeling, which introduces some uncertainty given the steady-state assumption.
- Only positive and neutral pressurization conditions are covered. Negatively pressurized (exhaust ventilation) is not covered by these equations.
- The range of outdoor temperature and relative humidity described in Section 4.2.3 is limited and does not cover temperature extremes or very low humidity found in the eight geographic locations studied in this dissertation.
- Aging / off-gassing of building materials was not accounted for in these correlations and thus they are limited to the first few years of operation of these test homes.

It is interesting to note that for both houses (WC-2 and WC-3), increasing λ_{tot} by 0.1 h^{-1} is approximately equivalent to reducing the indoor temperature, T_{in}, by 1 K (1.0, 1.2 respectively) in terms of reduction of C_{HCHO}. Hun & Jackson (2014) completed an analysis for a 3rd house which shows a similar result (increasing λ_{tot} by 0.1 h^{-1} was equivalent to reducing T_{in} by 1.3 K). If this relationship holds generally for a large number of houses, it could provide a relatively inexpensive alternative to ventilation control based on a real-time formaldehyde controller.

Such a control algorithm would require only one simultaneous measurement of λ_{tot}, T_{in} and C_{HCHO}. With this input the ventilation rate would be adjusted based on the T_{in} to provide the desired C_{HCHO}.

5.2 Role of Relative Humidity and Outdoor Temperature

It was surprising that RH_{in}, RH_{out}, and T_{out} did not improve the fit of the correlations for either house. This may be, for RH_{out} and T_{out}, due to the fact that the indoor conditions are not impacted by outdoor environmental conditions due to the very effective vapor barriers, sealing and significant thermal insulation in these house designs. For RH_{in}, the lack of correlation may be because of the range of RH_{in} covered by the data sets was small (41-61% RH in House WC-2 and 31-65% RH for House WC-3). An alternate explanation is that in previous studies (Matthews et al. 1987), formaldehyde based adhesives were in the form of urea formaldehyde (UF) that show significant increase in HCHO emission rates with increasing %RH due to hydrolysis reactions as well as increasing temperature which affects the vapor pressure and diffusion coefficient for formaldehyde. Frihart et al. (2012) compared formaldehyde emissions from UF adhesive and no added formaldehyde (NAF), soy based adhesive, particleboard and plywood under different temperature and humidity conditions. The NAF products had much lower overall HCHO emission rates and did not respond to changes in temperature or %RH nearly as much as the UF products.

Positive (+) pressurization during the winter in certain climate zones could lead to condensation of moisture inside the walls. In actual homes, steps to minimize positive (+) pressurization when indoor moisture levels (dew-point) are greater than the minimum wall, or window, temperature inside the vapor barrier are recommended. Such steps may include use of a variable speed energy recovery ventilator (ERV) with pressurization control, or adequate temperature and pressure controlled dampers to allow indoor air to escape to the outside to reduce any positive (+) pressurization during very cold outdoor conditions.

Based on the fact that the data used to obtain the correlations shown in Eqn. (5.1) and Eqn. (5.2) included only supply (+) ventilation or natural infiltration (without mechanical ventilation), for the modeling phase of this study, it is assumed that and Eqn. (5.1) and Eqn. (5.2) are valid for both neutral and positive pressurization and that pressurization is controlled in the homes to prevent condensation of moisture in the walls during the winter. These correlations are clearly NOT applicable to exhaust (-) ventilation – which is acknowledged to be the most common, and least cost, ventilation method in current use.

Despite the potential weakness of these correlations, especially for extreme climates that occur in hot/humid or cold/dry environments, for the two specific house designs, these correlations are thought to be reasonable for indoor conditions found in the majority of climate zones to be considered as, in these very energy efficient homes, the indoor conditions are separated from the outdoor conditions due to very effective vapor barriers, sealing and significant thermal insulation. The model includes humidity control (%RH = 27% when $T_{out} < 0\ ^{o}C$ and %RH ≤ 48% at all other times) of the indoor environment (which avoids humidity extremes).

Without humidity control, in cold or dry climate zones where RH_{in} may be very low and thus beyond the bounds of the data used to derive these correlations, it is expected that equations Eqn. (5.1 and (5.2) without humidity control would provide a “worst case” estimate for C_{HCHO}. Eqn. (5.1 and (5.2 are thought to provide a “worst case” at low humidity levels as, unlike previous researchers, no reduction in C_{HCHO} is seen or accounted for due to decreased %RH in Eqn. (5.1 and (5.2. Matthews et al. (1986) showed that C_{HCHO} decreased in test homes as %RH decreases. Frihart et al. (2012) showed that NAF products have only minimal reduction of emissions when %RH is reduced from 75 to 30% RH, i.e., compared to UF products which show significant reduction of emissions as humidity is reduced. Although the composition of adhesives used in the test houses is unknown, differences in the adhesives used in PWPs in these test houses from those in houses investigated in the 1980’s, when UF adhesives dominated the market, may account for not seeing a correlation between C_{HCHO} and %RH.

5.3 Visualization of Conditions Required to Achieve Specific RELs

Using Eq. (5.1 and Eq. (5.2, Table 5.1 and Table 5.2 provide a visual perspective on the combinations of T_{in} and λ_{tot} required to achieve any of the various HCHO RELs considered in this study for House WC-2 and House WC-3. The lowest REL of 7 ppb, can be achieved by setting the cooling set point, T_{in}, to 23.5 ºC (74 ºF) and increasing the λ_{tot} to 0.50 ACH in House 2 and 0.70 ACH in House 3, or other combination of T_{in} and λ_{tot} as shown in Table (5.1 and Table (5.2 respectively. These λ_{tot} are in general agreement with the 0.51-1.0 ACH suggested by Singer and Willem (2012) and the 0.5 ACH suggested by Sherman & Hodgson (2004) to achieve desired C_{HCHO}.

Table 5.1 Visualization of T_{in} & AER to achieve various RELs for HCHO in House WC-2

	C_{HCHO}, ppb											
AER, [ach] / T [C]	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
21.6	25.3	20.7	16.2	11.7	7.2	2.6	2.0	2.0	2.0	2.0	2.0	2.0
21.667	25.9	21.4	16.8	12.3	7.8	3.3	2.0	2.0	2.0	2.0	2.0	2.0
21.7	26.2	21.7	17.2	12.6	8.1	3.6	2.0	2.0	2.0	2.0	2.0	2.0
21.8	27.1	22.6	18.1	13.6	9.1	4.5	2.0	2.0	2.0	2.0	2.0	2.0
21.9	28.1	23.6	19.0	14.5	10.0	5.5	2.0	2.0	2.0	2.0	2.0	2.0
22.0	29.0	24.5	20.0	15.5	10.9	6.4	2.0	2.0	2.0	2.0	2.0	2.0
22.1	30.0	25.5	20.9	16.4	11.9	7.4	2.8	2.0	2.0	2.0	2.0	2.0
22.2	30.9	26.4	21.9	17.4	12.8	8.3	3.8	2.0	2.0	2.0	2.0	2.0
22.3	31.9	27.3	22.8	18.3	13.8	9.3	4.7	2.0	2.0	2.0	2.0	2.0
22.4	32.8	28.3	23.8	19.2	14.7	10.2	5.7	2.0	2.0	2.0	2.0	2.0
22.5	33.8	29.2	24.7	20.2	15.7	11.1	6.6	2.1	2.0	2.0	2.0	2.0
22.6	34.7	30.2	25.7	21.1	16.6	12.1	7.6	3.0	2.0	2.0	2.0	2.0
22.7	35.6	31.1	26.6	22.1	17.5	13.0	8.5	4.0	2.0	2.0	2.0	2.0
22.8	36.6	32.1	27.5	23.0	18.5	14.0	9.4	4.9	2.0	2.0	2.0	2.0
22.9	37.5	33.0	28.5	24.0	19.4	14.9	10.4	5.9	2.0	2.0	2.0	2.0
23.0	38.5	33.9	29.4	24.9	20.4	15.9	11.3	6.8	2.3	2.0	2.0	2.0
23.1	39.4	34.9	30.4	25.8	21.3	16.8	12.3	7.8	3.2	2.0	2.0	2.0
23.2	40.4	35.8	31.3	26.8	22.3	17.7	13.2	8.7	4.2	2.0	2.0	2.0
23.3	41.3	36.8	32.3	27.7	23.2	18.7	14.2	9.6	5.1	2.0	2.0	2.0
23.4	42.2	37.7	33.2	28.7	24.2	19.6	15.1	10.6	6.1	2.0	2.0	2.0
23.5	43.2	38.7	34.1	29.6	25.1	20.6	16.1	11.5	7.0	2.5	2.0	2.0
23.6	44.1	39.6	35.1	30.6	26.0	21.5	17.0	12.5	7.9	3.4	2.0	2.0
23.7	45.1	40.6	36.0	31.5	27.0	22.5	17.9	13.4	8.9	4.4	2.0	2.0
23.8	46.0	41.5	37.0	32.4	27.9	23.4	18.9	14.4	9.8	5.3	2.0	2.0
23.9	47.0	42.4	37.9	33.4	28.9	24.3	19.8	15.3	10.8	6.3	2.0	2.0
24.0	47.9	43.4	38.9	34.3	29.8	25.3	20.8	16.2	11.7	7.2	2.7	2.0
24.1	48.8	44.3	39.8	35.3	30.8	26.2	21.7	17.2	12.7	8.1	3.6	2.0
24.2	49.8	45.3	40.7	36.2	31.7	27.2	22.7	18.1	13.6	9.1	4.6	2.0
24.3	50.7	46.2	41.7	37.2	32.6	28.1	23.6	19.1	14.6	10.0	5.5	2.0
24.4	51.7	47.2	42.6	38.1	33.6	29.1	24.5	20.0	15.5	11.0	6.5	2.0
24.444	52.1	47.6	43.0	38.5	34.0	29.5	25.0	20.4	15.9	11.4	6.9	2.3
24.5	52.6	48.1	43.6	39.1	34.5	30.0	25.5	21.0	16.4	11.9	7.4	2.9
HCHO RELs:												
> WHO	> 80 ppb	WHO	80 ppb	Canada	40 ppb	FEMA/CDC/NIOSH		16 ppb	CA OEHHA	7 ppb		

Table 5.2: Visualization of Tin & AER to achieve various RELs for HCHO in House WC-3

AER, [ach] / T [C]	C_{HCHO}, ppb															
	0.11	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85
21.6	96.6	85.8	72.3	58.8	45.3	31.8	18.3	4.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
21.667	98.8	88.0	74.5	61.0	47.5	34.0	20.5	7.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
21.7	99.9	89.1	75.6	62.1	48.6	35.1	21.6	8.1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
21.8	103.2	92.4	78.9	65.4	51.9	38.4	24.9	11.4	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
21.9	106.5	95.7	82.2	68.7	55.2	41.7	28.2	14.7	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
22.0	109.8	99.0	85.5	72.0	58.5	45.0	31.5	18.0	4.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
22.1	113.1	102.3	88.8	75.3	61.8	48.3	34.8	21.3	7.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0
22.2	116.3	105.5	92.0	78.5	65.0	51.5	38.0	24.5	11.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
22.3	119.6	108.8	95.3	81.8	68.3	54.8	41.3	27.8	14.3	2.0	2.0	2.0	2.0	2.0	2.0	2.0
22.4	122.9	112.1	98.6	85.1	71.6	58.1	44.6	31.1	17.6	4.1	2.0	2.0	2.0	2.0	2.0	2.0
22.5	126.2	115.4	101.9	88.4	74.9	61.4	47.9	34.4	20.9	7.4	2.0	2.0	2.0	2.0	2.0	2.0
22.6	129.5	118.7	105.2	91.7	78.2	64.7	51.2	37.7	24.2	10.7	2.0	2.0	2.0	2.0	2.0	2.0
22.7	132.8	122.0	108.5	95.0	81.5	68.0	54.5	41.0	27.5	14.0	2.0	2.0	2.0	2.0	2.0	2.0
22.8	136.1	125.3	111.8	98.3	84.8	71.3	57.8	44.3	30.8	17.3	3.8	2.0	2.0	2.0	2.0	2.0
22.9	139.3	128.5	115.0	101.5	88.0	74.5	61.0	47.5	34.0	20.5	7.0	2.0	2.0	2.0	2.0	2.0
23.0	142.6	131.8	118.3	104.8	91.3	77.8	64.3	50.8	37.3	23.8	10.3	2.0	2.0	2.0	2.0	2.0
23.1	145.9	135.1	121.6	108.1	94.6	81.1	67.6	54.1	40.6	27.1	13.6	2.0	2.0	2.0	2.0	2.0
23.2	149.2	138.4	124.9	111.4	97.9	84.4	70.9	57.4	43.9	30.4	16.9	3.4	2.0	2.0	2.0	2.0
23.3	152.5	141.7	128.2	114.7	101.2	87.7	74.2	60.7	47.2	33.7	20.2	6.7	2.0	2.0	2.0	2.0
23.4	155.8	145.0	131.5	118.0	104.5	91.0	77.5	64.0	50.5	37.0	23.5	10.0	2.0	2.0	2.0	2.0
23.5	159.1	148.3	134.8	121.3	107.8	94.3	80.8	67.3	53.8	40.3	26.8	13.3	2.0	2.0	2.0	2.0
23.6	162.3	151.5	138.0	124.5	111.0	97.5	84.0	70.5	57.0	43.5	30.0	16.5	3.0	2.0	2.0	2.0
23.7	165.6	154.8	141.3	127.8	114.3	100.8	87.3	73.8	60.3	46.8	33.3	19.8	6.3	2.0	2.0	2.0
23.8	168.9	158.1	144.6	131.1	117.6	104.1	90.6	77.1	63.6	50.1	36.6	23.1	9.6	2.0	2.0	2.0
23.9	172.2	161.4	147.9	134.4	120.9	107.4	93.9	80.4	66.9	53.4	39.9	26.4	12.9	2.0	2.0	2.0
24.0	175.5	164.7	151.2	137.7	124.2	110.7	97.2	83.7	70.2	56.7	43.2	29.7	16.2	2.7	2.0	2.0
24.1	178.8	168.0	154.5	141.0	127.5	114.0	100.5	87.0	73.5	60.0	46.5	33.0	19.5	6.0	2.0	2.0
24.2	182.0	171.2	157.7	144.2	130.7	117.2	103.7	90.2	76.7	63.2	49.7	36.2	22.7	9.2	2.0	2.0
24.3	185.3	174.5	161.0	147.5	134.0	120.5	107.0	93.5	80.0	66.5	53.0	39.5	26.0	12.5	2.0	2.0
24.4	188.6	177.8	164.3	150.8	137.3	123.8	110.3	96.8	83.3	69.8	56.3	42.8	29.3	15.8	2.3	2.0
24.444	190.1	179.3	165.8	152.3	138.8	125.3	111.8	98.3	84.8	71.3	57.8	44.3	30.8	17.3	3.8	2.0
24.5	191.9	181.1	167.6	154.1	140.6	127.1	113.6	100.1	86.6	73.1	59.6	46.1	32.6	19.1	5.6	2.0

HCHO RELs:

> WHO	> 80 ppb	WHO	80 ppb	Canada	40 ppb	FEMA/CDC/NIOSH	16 ppb	CA OEHHA	7 ppb

5.4 Summary

Chapter 5 provides the empirical models which are the basis of all the energy modeling in Phase 2 of the dissertation shown visually in Figure 1.1. Data from Chapter 4 were used to determine empirical correlations for the concentration of formaldehyde (C_{HCHO}), indoor temperature (T_{in}) and air exchange rate (AER) for two unoccupied test homes. Key findings include:

- In these homes, relative humidity and outdoor temperature do not have a large impact on C_{HCHO}
- An interesting equivalent impact on C_{HCHO} of increasing the AER by 0.1 h^{-1} or decreasing T_{in} by ~1 ^{o}C (1.0 and 1.2) in these two homes was observed. A third home showed a similar equivalency (0.1 ↑ AER ~ 1.3 ^{o}C ↓ in T_{in}). This correlation may be unique to the materials and construction used in these very energy efficient homes. Further, the number of samples is far too low for any generalization. However, if replicated in a large number of homes, this observation may provide a cost effective means to control C_{HCHO} using a simple thermostat to control AER using a variable capacity ventilation system.
- Visualizations of the correlations between C_{HCHO}, T_{in}, and AER show general agreement with results suggested by others (Singer & Willem, 2012

and Sherman & Hodgson, 2004) that to achieve desired C_{HCHO}, AERs of 0.5 to 1.0 ACH may be required.

Chapter 6, and Appendix H, provide the details of the formaldheye removal and energy efficiency (FREE) model used in conjuction with the EnergyPlus™ model to calculate the energy used for 296 source reduction, ventilation and gas phase filtration scenarios reported in Chapter 8 using financial energy metrics described in Chapter 7.

Chapter 6 Energy Model Development and Application

The objective of this study is to determine energy requirements, greater than those associated with ASHRAE 62.2-2016 ventilation rates, required to achieve specific reference exposure limit (REL) concentrations (7, 16, 40, and 81 ppb) of formaldehyde (C_{HCHO}), in two simulated occupancy, energy efficient house designs. The corresponding analysis is completed for all eight Building America climate zones in the U.S.

The use of two computer models to calculate energy use and formaldehyde concentration (C_{HCHO}) in two test homes (WC-2 and WC-3 in Chapter 5) in eight U.S. climate zones is summarized in this chapter. Model equations are provided in Appendix H.

The first computer model, EnergyPlus™ v.8.5.0[4] (U.S. DOE Building Technology Office, 2012), is used to calculate total annual energy use for each house (GJ/y), including infiltration and ASHRAE 62.2-2016 minimum required mechanical ventilation with four sequential runs at each of eight locations as follows:

> Run 1: The objective of this run is to provide temperature and relative humidity profiles based on EnergyPlus™ for each zone to be used in

[4] EnergyPlus™ v 7.2.0.006 was used in the ORNL work shown in Appendix A

subsequent runs. While set-point indoor heating and cooling temperatures are fixed, the temperature profiles provided by EnergyPlus™ provide the temperature profile experienced in the house between the heating and cooling set-points.

Run 2: House with no mechanical ventilation (infiltration only). The temperature and relative humidity profiles obtained in Run 1 are used in Run 2 to obtain the infiltration profile.

Run 3: House only (no infiltration or mechanical ventilation). This run provides the energy used to thermally condition the house, including that used due to the heat loads from operation of appliances and lighting due to simulated occupancy as done in the ORNL work shown in Appendix A.

Run 4: House, infiltration, and ASHRAE 62.2-2016 minimum required mechanical ventilation with mechanical ventilation added to infiltration to simulate mechanical ventilation as an addition to the thermal load of the room rather than as added at a fixed supply temperature as in Run 1.

The second computer model [Formaldehyde Removal and Energy Efficiency (FREE)] is a spreadsheet model developed for this dissertation. FREE is used to calculate profiles of the hourly indoor concentration of formaldehyde ($C_{HCHO,i,n}$), and energy use for other simulated mechanical ventilation (mAER) and gas phase filtration (GPF) scenarios. The ASHRAE 62.2-2016 minimum required ventilation (base case) is calculated using the FREE model to compare results with base case results from EnergyPlus™. Formaldehyde concentration profiles for each hour of the year ($C_{HCHO,i,n}$) are calculated in the FREE model using the empirical models for C_{HCHO} developed in Ch. 5 for the two test homes studied at ORNL. Figure 6.1 shows the relationship between the two models.

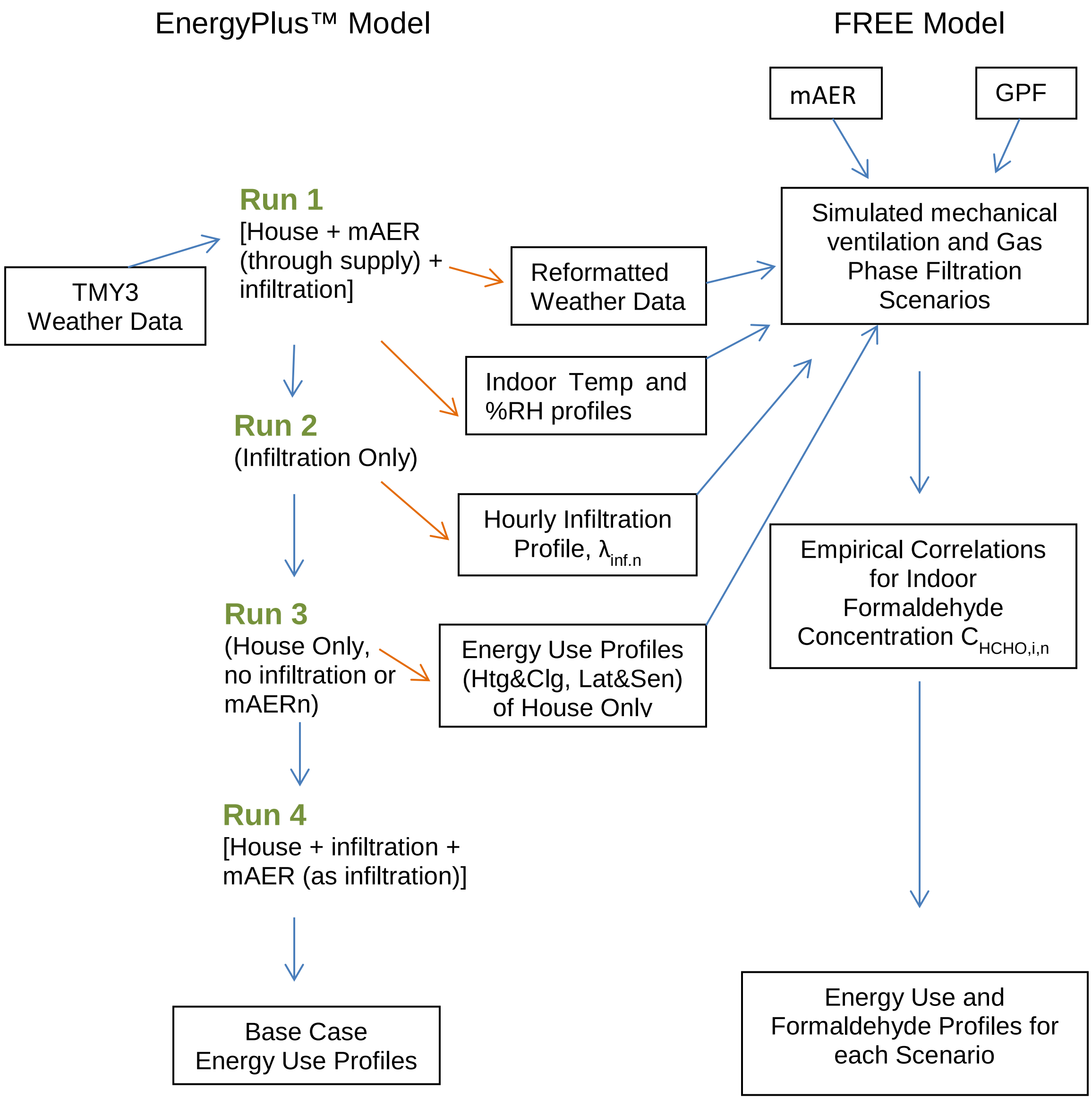


Figure 6.1: Relationship between EnergyPlus™ and FREE models

6.1 Conceptual Development

EnergyPlus™ was configured for the orientation, materials and design of each test house used in the Oak Ridge National Laboratory (ORNL) study and is used for energy modeling of the infiltration only and ASHRAE 62.2-2016 minimum required ventilation cases for this study of two test homes (WC-2 and WC-3 in Chapter 5) in eight separate climate zones. Figure 6.2 provides an overview of the variable inputs and outputs for EnergyPlus™. In both test homes, the heating, ventilating, and air conditioning (HVAC) system was inside the conditioned space.

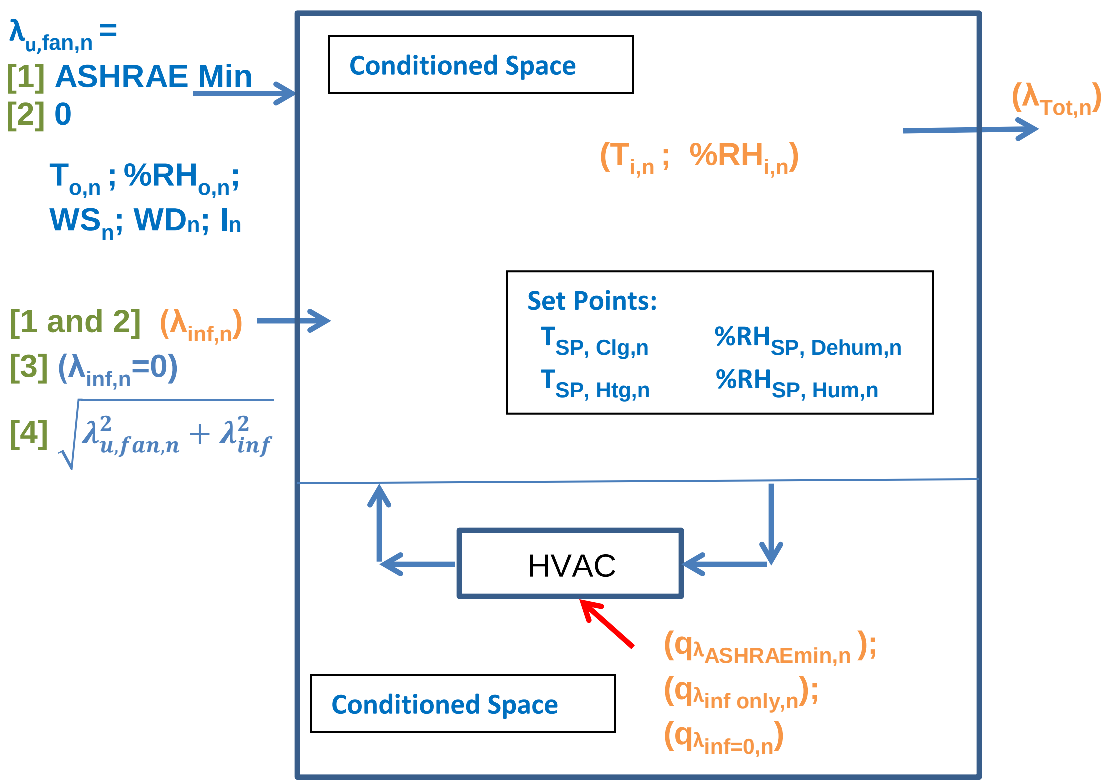


Figure 6.2: EnergyPlus™ **Inputs** and **(Outputs)**

The following are the **Inputs**, **(Outputs)** and **[EnergyPlus™ model runs]** listed in Figure 6.2:

Subscripts:

ASHRAEmin = ASHRAE 62.2-2016 minimum mechanical ventilation
Clg = cooling
Dehum = dehumidification
Htg = heating
Hum = humidification
i = indoor
inf = infiltration
o = outdoor
n = hour of the year (n=1 to 8,760)
SP = set point
u = unbalanced mechanical ventilation

$T_{SP, Clg,n}$ = cooling temperature set points, ^oC
$T_{SP, Htg,n}$ = heating temperature set points, ^oC
$\%RH_{SP,Dehum,n}$ = dehumidification set point, %RH
$\%RH_{SP,Hum,n}$ = humidification set point, %RH
$\lambda_{x,n}$ = air exchange rate, h^{-1}
x = inf; Tot; fan
$(q_{\lambda_{ASHRAEmin,n}})$ = HVAC energy for ASHRAE minimum mechanical ventilation (as infiltration), infiltration and house loads, kJ/h
$(q_{\lambda_{inf\ only,n}})$ = HVAC energy for infiltration only, kJ/h
$(q_{\lambda_{inf=0,n}})$ = HVAC energy for house loads only, kJ/h
$(T_{i,n}\ ;\%RH_{i,n})$ = indoor temperature and %RH

TMY3 Weather Data:
$T_{o,n}$ = outdoor temperature from TMY3 weather data, ^oC
$\%RH_{o,n}$ = outdoor %RH from TMY3 weather data
WS_n = wind speed, m/s
WD_n = wind direction
I_n = solar insolation, W/m^2

Key variable inputs include: hourly outdoor weather conditions using Typical Meteorological Year 3 (TMY3) datasets (Wilcox & Marion, 2008), heating, cooling, dehumidification, humidification set points, and mechanical ventilation rate. Key outputs include: annual energy use for climatic control for the minimum ASHRAE 62.2-2016 required mechanical ventilation rate or infiltration only scenario, hourly infiltration air exchange rates ($\lambda_{inf,n}$), and hourly indoor temperature and relative humidity ($T_{i,n}$, $\%RH_{i,n}$).

Infiltration is calculated using two sequential runs of EnergyPlus™. Run 1 uses infiltration and the minimum ASHRAE 62.2-2016 required mechanical ventilation rate (as supply air) to determine the hourly $T_{i,n}$ and $\%RH_{i,n}$ profiles which were between the fixed heating and cooling set-points depending on outdoor weather conditions, ventilation rates, solar insolation, windspeed and thermal lag of the structure Run 2 uses $T_{i,n}$ and $\%RH_{i,n}$ calculated in Run 1 as hourly set points ($T_{SP,clg,n} = T_{SP,htg,n} = T_{i,n}$ and $\%RH_{SP,dehum,n} = \%RH_{SP,hum,n} = \%RH_{i,n}$), sets mechanical ventilation to zero ($\lambda_{fan} = 0$), and calculates hourly HVAC energy use ($q_{\lambda_{inf\ only,n}}$) for the house for which all air exchange is due only to infiltration ($\lambda_{u,fan,n}$=0).

The variables described above relate to one house (H*); in one geographic location (g); for one cooling temperature set point ($T_{i,clg}$); for one ventilation scenario

($\lambda_{u,fan,n}$=0). This concept was applied to two different houses (H*= WC-2, WC-3) in eight different geographic locations (g=1–8).

Figure 6.3 shows the key components used in the FREE model to determine C_{HCHO} and additional energy use of other ventilation and gas phase filtration scenarios. The hourly infiltration air exchange rates ($\lambda_{inf,n}$), temperature ($T_{i,n}$), and relative humidity (%$RH_{i,n}$) determined using EnergyPlus™ are used as fixed parameters in the FREE model. Fixing these parameters allows a consistent comparison of energy use required to maintain identical indoor climatic conditions while mechanical ventilation or gas phase filtration rates are changed. Fixing $T_{i,n}$ and %$RH_{i,n}$ also permits calculation of energy use required to condition ventilation air due to mechanical ventilation by determining the difference in enthalpy between the indoor and outdoor atmospheres.

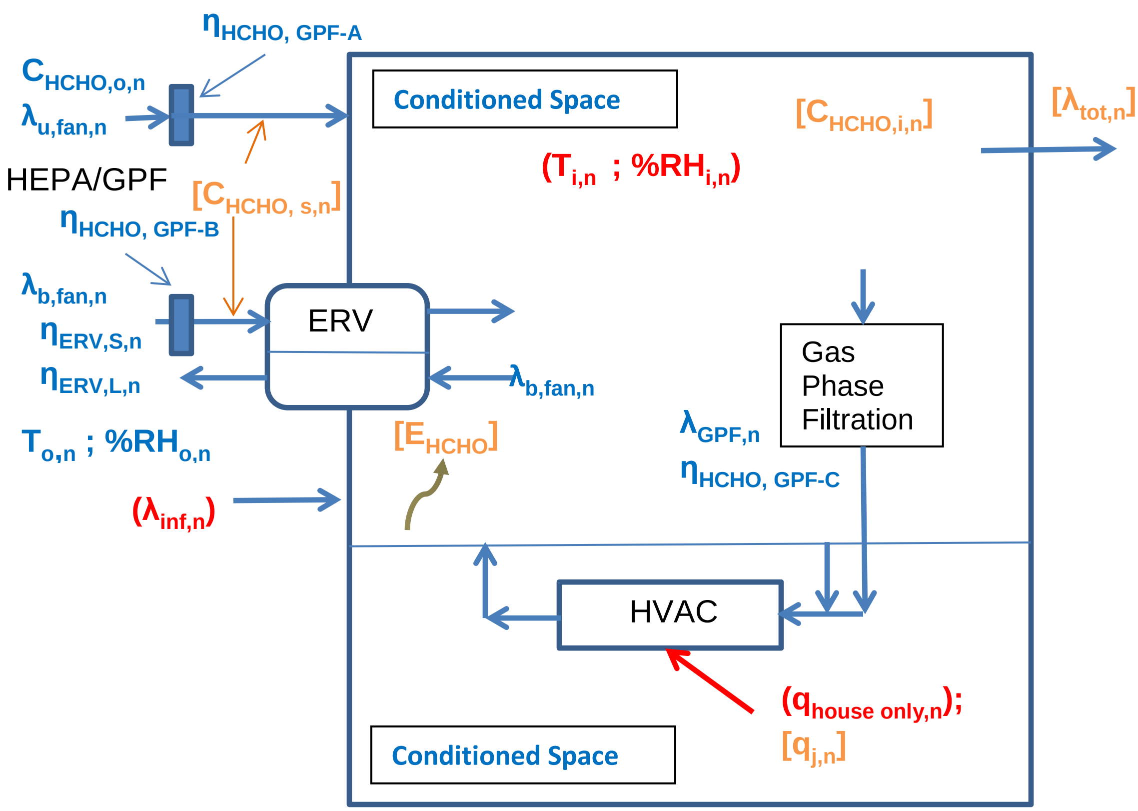


Figure 6.3: FREE Model **Inputs, (fixed parameters)** and **[Outputs]**

The following are the **Inputs** / **(Fixed parameters from EnergyPlus™)** / **[Outputs]** listed in Figure 6.2:

Subscripts:

- b, fan = balanced fan
- GPF-m = gas phase filter m where m = A, B, or C
- i = indoor
- inf = infiltration
- j = scenario j
- L = latent
- n = hour of the year (n=1 to 8760)
- o = outdoor

$_s$ = supply
$_S$ = sensible
$_{u,\ fan}$ = unbalanced fan

($T_{i,n}$) = fixed indoor temperature, ^oC from EnergyPlus™
($\%RH_{i,n}$) = fixed indoor relative humidity, %RH from EnergyPlus™
$C_{HCHO,x,n}$ = formaldehyde concentration, ppb
x = **o** ; **[s]** ; **[i]**
$\lambda_{x,n}$ = air exchange rate, h^{-1}
x = **(inf)** ; **u** ; **b** ; **GPF** ; **[tot]**
$\eta_{HCHO,\ GPF\text{-}m}$ = HCHO removal efficiency for GPF-m, unitless
$\eta_{ERV,x,n}$ = ERV energy efficiency, unitless
x = S ; L
($q_{house\ only,n}$) = **fixed hourly HVAC energy use for the house only, from EnergyPlus™, kJ/h**
[$q_{j,n}$] = **hourly HVAC energy use for ventilation/GPF scenario j, kJ/h**
[$E_{HCHO,\ n}$] = whole **house formaldehyde emission rate, mg/h**

The whole house formaldehyde emission rate, $E_{HCHO,n}$, in Figure 6.3, is not an input to FREE as the indoor concentration for HCHO ($C_{HCHO,i,n}$) is based on the empirical models developed in Ch. 5 with whole house air exchange rate ($\lambda_{tot,n}$) calculated from known infiltration ($\lambda_{inf,n}$) and mechanical ventilation rates ($\lambda_{u,fan,n}$, $\lambda_{b,fan,n}$). $E_{HCHO,n}$ is calculated as the product of the difference of the indoor and outdoor formaldehyde concentrations and volumetric flowrate, simply for comparison with emission rates reported by others, e.g., Turner et al. (2013).

The energy recovery ventilator (ERV) and gas phase filtration (GPF) system are not used in every ventilation / GPF scenario. When an ERV is used, balanced ventilation through the ERV is assumed. As shown in Figure 6.3, for the case of an ERV, any unbalanced ventilation air ($\lambda_{inf,n}$) is assumed to be made up by separate mechanical ventilation represented by $\lambda_{u,fan,n}$. In addition to insuring that there is no exhaust ventilation, but only supply, this approach prevents unbalanced flow through the ERV, which can decrease thermal efficiency of the ERV, as described by Mumma (2010). The assumption of perfectly balancing infiltration with mechanical ventilation ($\lambda_{inf,n} = \lambda_{u,fan,n}$) is for modeling purposes, but could be approached by use of an indoor/outdoor differential pressure sensor to control fan speed to balance infiltration.

The value associated with variables as described above for the FREE model apply to one house (H*); in one geographic location (g); for one set of fixed parameters ($T_{i,n}$; $\%RH_{i,n}$; $\lambda_{inf,n}$; $q_{\lambda inf,n}$), for one ventilation (always supply) scenario. No indoor materials (e.g. furnishings or different building materials) were changed in the houses during the sampling program. A summary of the nine scenarios (base case, 4 constant and 4 demand controlled mechanical ventilation scenarios all at T_{Clg} = 24.4 ^{o}C, modeled for both houses (H*= WC-2, WC-3) in all eight Building America climate zones is shown in Table 6.1 (total of 144 scenarios).

Table 6.1: Summary of Modeling Scenarios in all Climate Zones

Parameter	**Scenarios all at T_{clg} = 24.4 °C**	**# Scenarios**
House designs (H*)	House WC-2 and WC-3	
Geographic Locations / Climate Zones (g)	8 Building America Climate Zones	
Base case	**ASHRAE Ventilation**	16
Constant mechanical ventilation to achieve ≤ $C_{HCHO,i,n}$ for all n	$C_{HCHO,i,n}$: 81, 40, 16, 7 ppb	64
Demand controlled mechanical ventilation (DCV) to achieve ≤ $C_{HCHO,i,n}$ for all n	$C_{HCHO,i,n}$: 81, 40, 16, 7 ppb	64

Table 6.2 provides a summary of 152 additional modeling scenarios performed on a single house (WC-2) at a single location to show the impact of: lowering the cooling temperature set-point, using various constant mechanical ventilaton rates, reducing indoor HCHO emission rates (ER_{HCHO}), using of gas phase filtration (GPF), and use of an energy recovery ventilator (ERV) on energy use. House WC-2 was selected as it is the design most likely to be adopted by builders, whereas house WC-3 with phase change materials in the walls is least likely to be adopted by large builders. Finally, a sensitivity analysis is performed to show the impact of a constant elevated outdoor formaldehyde concentration ($C_{HCHO,o,n}$= constant). Austin was selected for most of these additional scenarios as it has the highest number of cooling degree days of all the cities studied. Los Angeles was selected

for the sensitivity analysis of $C_{HCHO,o,n}$, as it has the highest reported outdoor concentration for HCHO in the United States.

Table 6.2: Modeling Scenarios Limited to One House(WC-2)/Climate Zone

Parameter	Scenarios	Location	# Scenarios
Lower cooling set point ($T_{Clg,n}$)	T_{clg} = 23.44 ^{o}C (all other scenarios use 24.44 ^{o}C) ASHRAE Ventilation BC, Constant and DC V for $C_{HCHO,\ i,n}$ ≤ 81, 40, 16, 7 ppb	All	72
Constant mechanical ventilation (C mAER) (Using RMS and Improved Superposition)	ASHRAE Ventilation BC mAER = 0.166 h^{-1}	Austin	2
	CO_2 based: 600 ppm mAER = 0.295 h^{-1}		4
	mAER: 0.35; 0.5; 1.0 h^{-1}		12
Exploratory Scenarios Lower HCHO Emission Rate (ER) 25% reduction of ER_{HCHO} 50% Reduction of ER_{HCHO}	ASHRAE Ventilation BC, Constant and DC V for $C_{HCHO,\ i,n}$ ≤ 81, 40, 16, 7 ppb	Austin	18
Gas Phase Filtration $\lambda_{u,\ fan}$ [up to ASHRAE min] + GPF	Constant and DC GPF for $C_{HCHO,\ i,n}$ ≤ 81, 40, 16, 7 ppb	Austin	8
Energy Recovery Ventilator ERV-A + ($\lambda_{u,\ fan} = \lambda_{inf}$) and ERV-B + ($\lambda_{u,\ fan} = \lambda_{inf}$)	ASHRAE Ventilation BC, Constant and DC V for $C_{HCHO,\ i,n}$ ≤ 81, 40, 16, 7 ppb	Austin	18
Elevated $C_{HCHO,\ o}$ Sensitivity Analysis $\lambda_{u,\ fan}$	ASHRAE Ventilation BC, Constant and DC GPF for $C_{HCHO,\ i,n}$ ≤ 81, 40, 16, 7 ppb $C_{HCHO,o}$ = 10,15 ppb	Los Angeles	18

BC = Base Case; C = Constant; DC = Demand Controlled; ER = Emission Rate; V=Ventilation; GPF = Gas Phase Filtration; RMS = Root Mean Square

6.2 Differences between this Study and that Reported by Hun et al. (2013)

The objective of the work reported by Hun et al. (2013a, b) was to report C_{HCHO} and energy use in two test houses in one location (Oak Ridge, TN) when defined ventilation flowrates were used as specified in ASHRAE 62.2-2010. In contrast, the objective of this study is to determine optimal combinations of source reduction, indoor temperature (T_{in}), and mechanical ventilation (λ_{fan}) to never exceed, on an hourly basis, the RELs of interest.

To accomplish this objective, the same empirical correlations between C_{HCHO}, λ_{tot}, and T_{in} to model C_{HCHO} reported by Hun et al. (2013a), described in Chapter 5, and modified for differing outdoor C_{HCHO} in Appendix H were applied. The EnergyPlus™ model reported by Hun et al. (2013a) is used to obtain infiltration rates for use in the FREE model. In Hun et al. (2013a), site, and year specific weather data, were used to calibrate the λ_{inf} calculations in the EnergyPlus™ model for each house. The same calibrated EnergyPlus™ models for each house were used in this study. Additional details on how the calibration was done are presented in Appendix H.

The largest difference, between this work and that of Hun et al. (2013a), is that in this work, the EnergyPlus™ model was modified to treat mechanically ventilated outdoor air as an infiltration load. This approach treats mechanical ventilation as a room load (i.e., brought to room temperature), which is typical of a residential HVAC system rather than a load introduced at a fixed supply temperature (i.e. brought to the temperature of a fixed supply temperature), which is more typical of a commercial HVAC system. This change significantly reduces the energy cost of mechanically ventilated air and more closely approximates typical residential HVAC systems. This change to EnergyPlus™ was only needed for Run 4 of the EnergyPlus™ model as shown in Figure 6.1 where energy use for mechanically ventilated air (the energy to raise outdoor air to room temperature) was added to that needed for the house in addition to infiltration.

Different base case conditions were used in this study to incorporate changes in minimum ventilation rates between the ASHRAE 62.2-2010 rates used by Hun et al. (2013a) and the ASHRAE 62.2-2016 rates used in this study. Maximum relative humidity conditions recommended by the U.S. EPA (USEPA, 2013a) for controlling moisture in buildings and a minimum relative humidity of 20% RH recommended by AST (2015) to prevent electrostatic discharge are also a new addition in this study. TMY3 weather data from the Knoxville, TN, airport was used rather than site specific (Oak Ridge, TN) weather data, i.e., as used by Hun et al. (2013a). This work also expands on the work of Hun et al. (2013a) by evaluating the energy use required to obtain defined C_{HCHO} if the same two test houses were located in eight locations that represent each of the eight Building America climate zones.

6.3 Summary

The use of two computer models (EnergyPlus™ and FREE) used to calculate hourly and annual energy use in the two test houses (WC-2 and WC-3) studied at ORNL was described in this chapter. Model equations are presented in Appendix H. The models allow energy use of houses of the same design to be calculated in all eight climate zones in the U.S. The U.S. DOE EnergyPlus™ model and the FREE (Formaldeyde Removal and Energy Efficiency) model developed by the author show an average difference over all sites between the two models of 2% or less. The greater variation in house WC3 is thought to be due to the thermal lag from the phase change materials in the walls. For consistency, only FREE model results will be used for comparion purposes in future chapters.

This chapter, in addition to the detailed description of the model developmend in Appendix H, describes the two models used in Phase 2 of the dissertation shown visually in Figure 1.1 dealing with Energy. Chapter 7 will form the bridge between electrical energy use and financial metrics to form the basis for reporting the value of the source reduction, ventilation, and gas phase filtration scenaries shown in Table 6.1 and 6.2 and reported in Chapter 8.

Chapter 7 Suite of Metrics to Quantify Energy Consumption

The practical outcomes of this study are to develop a suite of metrics to quantify whole house HVAC energy consumption for the two unoccupied test homes studied when: (1) ASHRAE 62.2-2016 ventilation rates are used, and (2) additional ventilation and/or gas phase filtration (GPF) is used to achieve specified RELs for HCHO which are below those achieved with ventilation to ASHRAE 62.2-2013.

Previous researchers have assumed that formaldehyde emission rates are constant throughout the year. An example is the work of Turner et al. (2013), who used the Offermann (2009) data base. This dissertation is the first study known to the author that correlates varying formaldehyde emission rates throughout the year with energy use. Further, this study quantifies potential energy savings of using variable speed ventilation fans with formaldehyde controllers to assure specified $C_{HCHO,n} \leq 81, 40, 16, 7$ ppb are achieved for every hour throughout the year.

Varying mechanical ventilation based on demand controlled ventilation of measured HCHO concentrations presents a valuable opportunity to save energy while achieving specified metrics of IAQ. To verify the energy savings potential and quantify the value of demand controlled ventilation using HCHO as a metric, many homes in diverse climate zones need to be monitored for an entire year with accurate real-time formaldehyde monitors in addition to real-time weather and HVAC energy use.

7.1 Area and Volume Based Annual Energy Consumption

Area normalized Annual Energy Consumption ($AEC_{A,\ HCHO=\ REL\ in\ ppb}$) with units of MJ/m^2 and volume normalized Annual Energy Consumption ($AEC_{V,\ HCHO\ =REL\ in\ ppb}$) with units of MJ/m^3 are calculated for the base case and for specified RELs (7, 16, 40, and 81 ppb) for HCHO as shown in Eq. *7.1* and Eq. 7.2.

$$AEC_{A,HCHO=\ REL\ in\ ppb} = {}^{AEC}/_{A} \qquad (7.1)$$

$$AEC_{V,HCHO=\ REL\ in\ ppb} = {}^{AEC}/_{V} \qquad (7.2)$$

where,

AEC = Annual energy consumption, MJ/y

A = House floor Area, m^2

V = occupied volume of house, m^3

7.2 Area and Volume Based Annual Energy Consumption using TDD

The area and volume normalized AEC are normalized by Total Degree Days with a base temperature of 18.3 ^{o}C (TDD18.3) ($AEC_{a,\ HCHO=\ REL\ in\ ppb,\ TDD18.3}$; $AEC_{v,HCHO=\ REL\ in\ ppb,\ TDD18.3}$) shown in Eqn. 7.3 and Eqn. 7.4.

$$\mathrm{AEC}_{\mathrm{A,HCHO=\,REL\ in\ ppb,TDD18.3}} = {}^{AEC_{A,HCHO=\,REL\ in\ ppb}}\!/_{TDD18.3} \quad (7.3)$$

$$\mathrm{AEC}_{\mathrm{V,HCHO=\,REL\ in\ ppb,TDD18.3}} = {}^{AEC_{V,HCHO=\,REL\ in\ ppb}}\!/_{TDD18.3} \quad (7.4)$$

where,

$AEC_{A,\ HCHO=REL\ in\ ppb}$ = floor area based annual energy consumption to achieve specific REL, $MJ/m^2/y$

$AEC_{A,\ HCHO=REL\ in\ ppb,\ TDD18.3}$ = floor area based annual energy consumption to achieve a specific REL normalized to TDD18.3, $MJ/m^2/TDD18.3/y$

$AEC_{V,\ HCHO=REL\ in\ ppb}$ = occupied volume based annual energy consumption to achieve specific REL, $MJ/m^2/y$

$AEC_{V,\ HCHO=REL\ in\ ppb,\ TDD18.3}$ = occupied volume based annual energy consumption to achieve a specific REL normalized to TDD, $MJ/m^2/TDD18.3/y$

A = house floor area, m^2

V = occupied volume of house, m^3

TDD18.3 = total degree days with a base temperature of 18.3 ^oC

Heating and cooling degree day data, obtained from ASHRAE (2013d) were shown previously in Table 6.7.

Total Degree Days with a base temperature of 18.3 ^{o}C (TDD18.3) are calculated as shown in Eqn. 7.5

$$TDD18.3 = HDD18.3 + CDD18.3 \tag{7.5}$$

where,

TDD18.3 = total Degree Days with 18.3 ^{o}C base temperature

HDD18.3 = heating degree days with 18.3 ^{o}C base temperature

CDD18.3 = cooling degree days with 18.3 ^{o}C base temperature

7.3 Normalized *mAER* to Achieve Desired HCHO RELs

Annual average ventilation rates normalized to a base case of ASHRAE 62.2-2016 required ventilation rates required to achieve any of the specified RELS for HCHO are calculated as shown in Eqn. 7.6.

$$\lambda_{Ann,n,HCHO=REL\ in\ ppb} = {\lambda_{Ann,mAER,HCHO=REL\ in\ ppb}}\Big/{\lambda_{ASHRAE\ 62.2-2016,mAER}} \tag{7.6}$$

where,

$\lambda_{Ann,n,HCHO=REL\ in\ ppb}$ = normalized annual average mechanical ventilation rate, mAER for the given REL normalized to the ASHRAE 62.2-2016 minimum required mechanical ventilation, unitless

7.4 Energy Consumption Normalized to FEMA Base Case

Energy consumption normalized to the Federal Emergency Management Agency (FEMA) required HCHO concentration (16 ppb) is calculated as shown in Eqn. 7.7.

$$AEC_{A,HCHO=REL\ in\ ppb,FEMA} = AEC_{A,HCHO=REL\ in\ ppb} \Big/ AEC_{A,HCHO=16\ ppb}. \qquad (7.7)$$

where,

$AEC_{A,\ HCHO=REL\ in\ ppb}$ = floor area based annual energy consumption to achieve a specific REL, MJ/m^2/y

$AEC_{A,\ HCHO=REL\ in\ ppb,\ FEMA}$ = floor area based annual energy consumption to achieve a specific REL normalized to FEMA required C_{HCHO}, [unitless]

A = house floor area, m2

7.5 Non-Capital Cost (NCC) of a Scenario

This non-capitcal cost (NCC) analysis considers total energy cost used in the scenarios desrcribed in Tables 6.1 and 6.2. This NCC analysis is limited to energy costs, societal cost of carbon (SCC) used to generate the electricity in each climate zone/city studied, and the health risk associated with exposure to formaldehyde using the DALYs that were discussed in Chapter 3. This analysis does not include the capital, installation, or maintenance cost of additional ventilation, cooling, GPF, or HVAC control equipment. However, when the cost of electricity and other NCC are known, the value of any additional equipment, installation, and maintenance can be estimated from the energy savings, avoidance of societal cost of carbon and reduction in health risk of one case compared with another.

For this analysis, the current retail prices of electricity obtained from U.S. Energy Information Administration (2015) for each of the sites as shown in Table 7.1 are used.

Table 7.1: Price of electricity by site

City, State/County	Average Price of Electricity (₵/kWH), year-to-date through July 2015 U.S. EIA (2015)
Amarillo, TX / Potter & Randall	11.76
Arcata, CA / Humboldt	16.80
Austin, TX / Travis	11.76
Buffalo, NY / Erie	18.86
Fairbanks, AK / Fairbanks North Star	19.97
Houghton, MI / Houghton	14.21
Los Angeles, CA / Los Angeles	16.8
Knoxville, TN / Anderson & Roane	10.71
U.S. Average*	12.59
Minimum	10.71
Maximum	19.97

* Rolling 12-month average ending in July 2015 is 12.62 ₵/kWh

7.5.1 Societal Cost of Electricity

To estimate the total cost of electricity, the regional cost of electricity was obtained from the U.S. Energy Information Administration (2015) for each of the sites as shown above in Table 7.1 and adjusted for the value of carbon as described below.

Carbon dioxide equivalent (CO_{2e}) emissions, presented in mt/kWh and grid losses (decimal) for each site were obtained from The Emissions and Generation Resource Integrated database (eGRID) (U.S. EPA, 2015a). Total carbon use for each kWh of electricity used at each site were calculated using the method described by the U.S. EPA (2012b) to account for emission rates and line losses using Eq. 7.8 and are shown in Table 7.2.

$$ER_c = \frac{ER_g}{(1-GGL)} \tag{7.88}$$

where,

ER_c = emission rate from combined generation and line losses, metric tons/kWh

ER_g = eGRID generation based output emission rate, metric tons/kWh

CGL = eGRID grid gross loss factor (decimal)

Table 7.2: Combined Generation and Line Loss CO_2e Emission Rates

City, State/County	eGRID Subregion (U.S. EPA, 2015b)	Carbon dioxide equivalent (CO_2e) ER_g (mt/kWh) (U.S. EPA, 2015b)	Grid Gross Loss (decimal) CGL (U.S. EPA, 2015b)	Carbon dioxide equivalent (CO_2e) ERc (mt/kWh)
Amarillo, TX / Potter & Randall	SPSO	0.000608	0.0576	0.0006456
Arcata, CA / Humboldt	CAMX	0.000257	0.0576	0.0002727
Austin, TX / Travis	ERCT	0.000452	0.0703	0.0004858
Buffalo, NY / Erie	NYUP	0.000162	0.0917	0.0001778
Fairbanks, AK / Fairbanks North Star	AKGD	0.000501	0.0866	0.0005481
Houghton, MI / Houghton	RFCW	0.000546	0.0917	0.0006010
Los Angeles, CA / Los Angeles	CAMX	0.000257	0.0576	0.0002727
Knoxville, TN / Anderson & Roane	SRTV	0.000529	0.0917	0.0005825
Average		0.000450	0.0833	0.0004904
Minimum		0.0001615	0.0576000	0.0001778
Maximum		0.0006084	0.0917000	0.0006456

While a full analysis of the value of reducing CO_2, referred to as the societal cost of carbon (SCC) is beyond the scope of this study, obtaining the range of currently discussed values ($2 to $220/mt CO_2) provides input on what the value of technologies and practices to reduce the use of electricity discussed in this study are under a variety of scenarios. Estimates of the value of reducing emissions of CO_2 and, to a lesser extent, other greenhouse gases (GHG) when included as carbon dioxide equivalents (CO_2e) were obtained from four primary sources:

1. The currently traded value of California Carbon Futures (Climate Policy Initiative, 2015)
2. The U.S. EPA's analysis of the societal cost of CO_2 (U.S. EPA, 2015c; United States Government Interagency Working Group on Carbon, 2015). Values are presented by the EPA in 2014 dollars.
3. A recent journal article which proposes an upward adjustment of the SCC based on the impact of climate change on sustained gross domestic product (GDP) growth (which leads to lower discount rates) and the rate of adaptation to rising global temperature (Moore & Diaz, 2015).
4. A report by the Organization for Economic Cooperation and Development that reviews carbon tax rates from 13 different countries (OECD, 2013a, 2013b).

The currently traded value (2015$) of California Carbon futures is $12.75 ± $0.11 (1 s.d.) for a metric ton (mt) of carbon dioxide equivalent (CO_2e). This value is the average price per mt of California Carbon Dec 2015 Allowance Futures from 1/2/15

- 10/9/15 from prices published on the California Climate Dashboard (Climate Policy Initiative, 2015).

The societal cost of carbon (SCC), defined by the U.S. EPA in terms of \$/mt CO_2 provides a method to monetize the benefit to society due to reduction in the amount of CO_2 emitted during production of electricity (or saved by reduction in use of electricity). The SCC is used to estimate the climate benefits of government rulemaking (U.S. EPA, 2015c). Four U.S. EPA model scenarios shown in Table 7.4 are presented using the average or 95th percentile value of the SCC with different discount rates, all in 2014\$ (United States Government Interagency Working Group on Carbon, 2015). The GDP Implicit Price Deflator for the end of the 2nd Quarter of 2015 is only 0.909% above that of 2014\$ (Bureau of Economic Analysis, 2015). Using the two significant digit values that the EPA reports (U.S. EPA, 2015c) for the SCC, this can only be seen for the average SCC value using a 2.5% discount rate and the 95th percentile value for the SCC using a 3% discount rate which have been adjusted upward.

The Organization for Economic Cooperation and Development (OECD) reports that 13 countries have a carbon tax (OECD, 2013a, 2013b) ranging from US \$2 per metric ton of CO_2 equivalent (tCO_2e) in Japan to US \$168 per tCO_2e in Sweden (OECD, 2013a, 2013b) .

The SCC of carbon reported by: 1) the traded California Carbon futures price; 2) the EPA analysis prices; and 3) those cited by Moore and Diaz discussed above are shown as ₵/kWh for each geographic site in Table 7.3. The average SCC ranges from 0.6₵/kWh to 10.8 ₵/kWh. Note that the average SCC is 8.2 ₵/kWh using the current Swedish value for SCC of $168/mt.

Table 7.3: Societal Cost of Carbon by Site

City, State/County	Traded	Societal Cost of Carbon emitted in 2015					
	CPI (2015)	U.S. EPA (2015) Discount rate / Statistic				Moore and Diaz (2015)	
	CAC-2015	5% Avg	3% Avg	2.5% Avg	3% 95th %ile	DICE-2R	gro-DICE
	$/mt of $CO2$						
	$12.75	$12	$40	$63	$121	$33	$220
	CO_2e Cost (₵/kWH)						
Amarillo, TX / Potter & Randall	0.8	0.8	2.6	4.1	7.8	2.1	14.2
Arcata, CA / Humboldt	0.3	0.3	1.1	1.7	3.3	0.9	6.0
Austin, TX / Travis	0.6	0.6	1.9	3.1	5.9	1.6	10.7
Buffalo, NY / Erie	0.2	0.2	0.7	1.1	2.2	0.6	3.9
Fairbanks, AK / Fairbanks North Star	0.7	0.7	2.2	3.5	6.6	1.8	12.1
Houghton, MI / Houghton	0.8	0.7	2.4	3.8	7.3	2.0	13.2
Los Angeles, CA / Los Angeles	0.3	0.3	1.1	1.7	3.3	0.9	6.0
Knoxville, TN / Anderson & Roane	0.7	0.7	2.3	3.7	7.0	1.9	12.8
Average	**0.6**	**0.6**	**2.0**	**3.1**	**5.9**	**1.6**	**10.8**
Minimum	**0.2**	**0.2**	**0.7**	**1.1**	**2.2**	**0.6**	**3.9**
Maximum	**0.8**	**0.8**	**2.6**	**4.1**	**7.8**	**2.1**	**14.2**

The total value of electricity including SCC by site is shown as ₵/kWh for each geographic site in Table 7.4.

Table 7.4: The Total Value of Electricity Including SCC by Site

City, State/County	Traded	Societal Cost of Carbon emitted in 2015					
	CPI (2015)	U.S. EPA (2015) Discount rate / Statistic				Moore and Diaz (2015)	
	CAC-2015	5% Avg	3% Avg	2.5% Avg	3% 95th %ile	DICE-2R	gro-DICE
	$/mt of CO2						
	$12.75	$12	$40	$63	$121	$33	$220
	Total Value of Electricity Including SCC by site (₵/kWH)						
Amarillo, TX / Potter & Randall	**12.6**	**12.5**	**14.3**	**15.8**	**19.6**	**13.9**	**26.0**
Arcata, CA / Humboldt	**17.1**	**17.1**	**17.9**	**18.5**	**20.1**	**17.7**	**22.8**
Austin, TX / Travis	**12.4**	**12.3**	**13.7**	**14.8**	**17.6**	**13.4**	**22.4**
Buffalo, NY / Erie	**19.1**	**19.1**	**19.6**	**20.0**	**21.0**	**19.4**	**22.8**
Fairbanks, AK / Fairbanks North Star	**20.7**	**20.6**	**22.2**	**23.4**	**26.6**	**21.8**	**32.0**
Houghton, MI / Houghton	**15.0**	**14.9**	**16.6**	**18.0**	**21.5**	**16.2**	**27.4**
Los Angeles, CA / Los Angeles	**17.1**	**17.1**	**17.9**	**18.5**	**20.1**	**17.7**	**22.8**
Knoxville, TN / Anderson & Roane	**11.5**	**11.4**	**13.0**	**14.4**	**17.8**	**12.6**	**23.5**
Average	**15.7**	**15.6**	**16.9**	**17.9**	**20.5**	**16.6**	**25.0**
Minimum	**11.5**	**11.4**	**13.0**	**14.4**	**17.6**	**12.6**	**22.4**
Maximum	**20.7**	**20.6**	**22.2**	**23.4**	**26.6**	**21.8**	**32.0**

For this study, the total value of electricity savings is taken as the average cost of electricity at the site plus the SCC at $40/mt of CO_2 as shown in the highlighted column of Table 7.4.

For the modelled sites, the average total price of electricity including SCC ranges from 15.7 to 25.0 ₵/kWh (Table 7.4) and 10.7 to 20.7 ₵/kWh without the SCC (Table 7.1). These values are compared with the average price of electricity to residential customers for the 19 most expensive states and the average electricity price in the U.S. that does not include the SCC in Table 7.5 using prices from the September 2015 Electric Power Monthly report with Data for July 2015 (U.S. Energy Information Administration, 2015) . Note that the full range of average total price of electricity including SCC for the modeled sites is within the current average prices of the top 11 states that do not include the SCC.

Table 7.5: Average Residential Cost of Electricity by State Without SCC

Rank by Price	**State**	**Residential Price of Electricity ₵/kWh**
1	Hawaii	30.93
2	Connecticut	21.74
3	Massachusetts	20.61
4	Alaska	19.97
5	New Hampshire	19.14
6	Rhode Island	18.98
7	New York	18.86
8	Vermont	16.92
9	California	16.80
10	New Jersey	15.94
11	Maine	15.87
12	Wisconsin	14.34
13	Michigan	14.21
14	Maryland	13.64
15	Delaware	13.58
16	Pennsylvania	13.52
17	District of Columbia	13.20
18	Nevada	12.96
19	New Mexico	12.62
20	**U.S. Average**	**12.59**

7.6 Optimization of Annual Energy Use

A constant, average outdoor concentration of formaldehyde $C_{HCHO,OA}$ was assumed with city-specific measurements used where available (i.e., 2 ppb in Oak Ridge and a range from 1-15 ppb in Los Angeles). Where no city-specific data are available, 5.1 ppb based on the RIOPA study as reported by Salthammer (2013) was assumed. For rural areas (Houghton, MI, Arcata, CA and Fairbanks, AK), 1 ppb was assumed. Assumed Outdoor formaldehyde $C_{HCHO,o}$ used are summarized in Table 7.6.

Table 7.6: Summary of Outdoor Formaldehyde Concentrations, $C_{HCHO,o}$

City	$C_{HCHO,o}$ ppb
Amarillo	5
Arcata	1
Austin	5
Buffalo	5
Fairbanks	1
Houghton	1
Los Angeles	5 to 15*
Knoxville	2

* Sensitivity analysis

When $C_{HCHO,o}$ is greater than the desired $C_{HCHO,i}$, ventilation is not a viable control mechanism for HCHO. However, in order to provide ventilation for other contaminants (i.e. CO_2, bioeffluents, etc.), code minimum ventilation will still be required. When $C_{HCHO,o}$ is greater than desired $C_{HCHO,i}$, all outdoor air will need to be filtered to remove HCHO as well as other potential contaminants (i.e. O_3 and $PM_{2.5}$). A sensitivity analysis of a range (5-15 ppb) of assumed constant outdoor average $C_{HCHO,o}$ for Los Angeles using constant mechanical ventilation at the minimum ASHRAE 62.2-2016 mechanical ventilation rate and constant and demand controlled GPF is performed in Chapter 8. The objective of this sensitivity analysis is to show the energy use impact of elevated $C_{HCHO,o}$ on achieving desired HCHO RELs.

7.7 Summary

Chapter 7 continues Phase 2, which was shown visually in Figure 1.1, of the dissertation by providing the bridge between energy use and energy cost. This energy cost, in addition to the economic value of the DALYs developed in Phase 1 of the dissertation as shown in Chapter 3 provides the value of the source reduction, ventilation and gas phase filtration which are reported in Chapter 8.

Chapter 8 Results of Energy Model Applications

This chapter presents the results of the modeling performed using the U.S. DOE's EnergyPlus™ and author-developed FREE (Formaldehyde Removal and Energy Efficiency) models developed in Ch. 6. The scenarios described in this chapter follow those summarized in Tables 6.1 and 6.2. The empirical models for indoor formaldehyde concentration ($C_{HCHO,i}$) using indoor temperature (T_{in}) and total air exchange rate (λ_{tot}) were described in Ch. 5. Metrics used to quantify energy consumption in house WC-2 in Austin were described in Ch. 7. Appendix H contains tables of all data used in the figures in this chapter as well as supplemental modeling results.

8.1 Energy Use for House WC-2 and WC-3 in all Climate Zones

Energy use for house WC-2 and WC-3 were modeled in eight different cities representing all eight ASHRAE climate zones. House WC-2 is the lower formaldehyde emission rate (ER_{HCHO}) house and WC-3 is a higher ER_{HCHO} house. The base case for each city uses constant mechanical ventilation at the minimum ASHRAE 62.2-2016 required mechanical ventilation (mAER) rate for each city. In addition, thermal energy use required to achieve desired indoor formaldehyde reference exposure limits (HCHO REL) using both constant (C) and demand controlled (DC) (based on $C_{HCHO,i}$) ventilation were calculated as shown in Figure

8.1 and 8.2 for house WC-2 and Figure 8.3 and 8.4 for house WC-3. These scenarios where run using a summer cooling temperature (T_{clg}) of 24.4 ^oC.

All other scenarios were run on house WC-2 as, of the two houses studied, the building design, materials and techniques used in this house are most likely to be used by volume residential home builders across the country.

Figure 8.1: WC-2 T_{clg}=24.4 ^oC –Thermal Energy Use – C mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

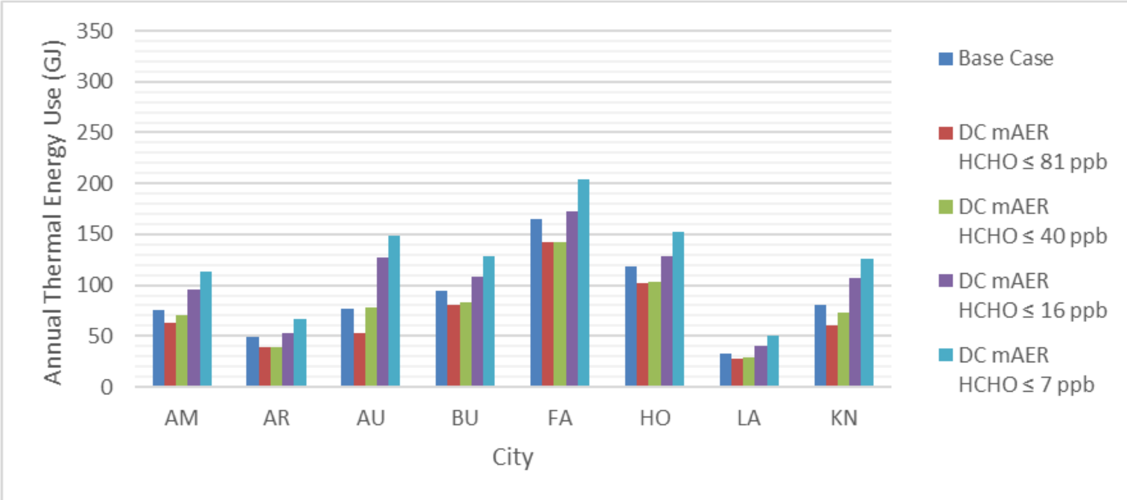


Figure 8.2: WC-2 T_{clg}=24.4C–Th. Energy Use – DC mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

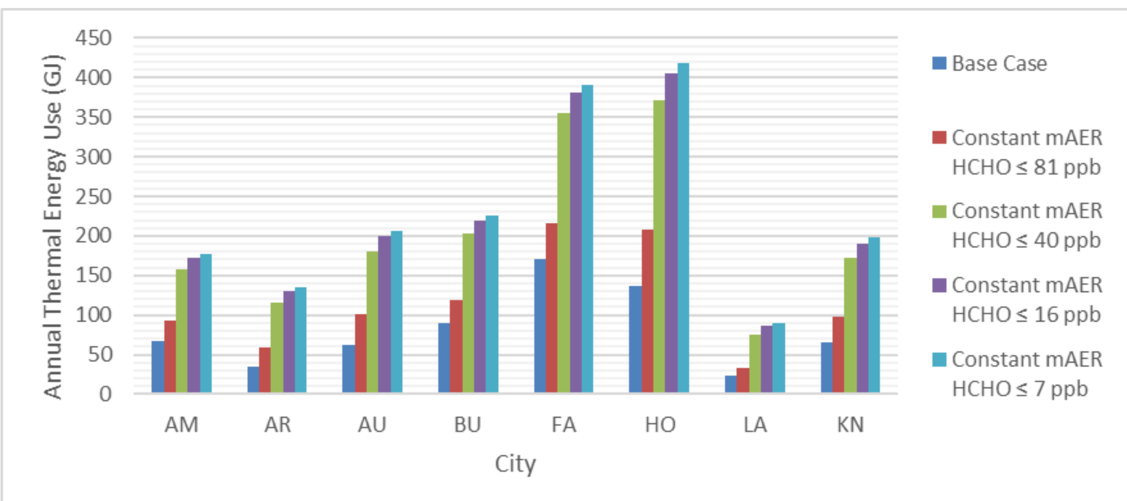


Figure 8.3: WC-3 T_{clg}=24.4C – Th. Energy Use – C mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

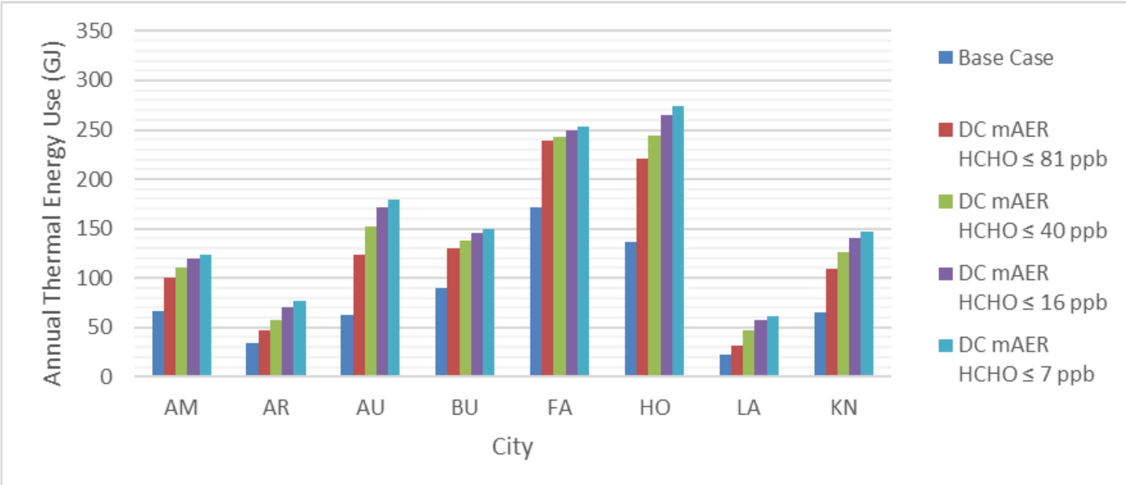


Figure 8.4: WC-3 T_{clg}=24.4C–Th. Energy Use – DC mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

The key point from Figures 8.1-8.4 are that demand controlled ventilation can significantly reduce total annual energy use in most cases while controlling indoor concentrations of formaldehyde to below desired reference exposure limits (RELs). An additional observation is that the base case ventilation energy use exceeds that required to keep $C_{HCHO} \leq 81$ ppb in all climate zones. When demand controlled ventilation is used, the current ASHRAE ventilation rates use more energy than is required using demand controlled ventilation to keep $C_{HCHO} \leq 40$ ppb in all climate zones. In these cases, the annual average ventilation rate is less than the ASHRAE required minimum.

8.2 Impact of Reduced Cooling Temperature – WC-2 in all Climate Zones

Cooling temperature (T_{clg}) was reduced to explore the impact of lower summer temperature on annual energy consumption and $C_{HCHO,n}$.

Figure 8.5 and 8.6 show the thermal energy used to condition house WC-2 when the cooling temperature set point was reduced by 1 ^oC for constant and demand controlled ventilation, respectively. Reducing the summer cooling temperature set point (T_{clg} = 23.3 ^oC) saved energy vs. using additional ventilation air at the base case cooling temperature set point (T_{clg} = 24.4 ^oC) to achieve the criteria $C_{HCHO,n} \leq$ 40, 16, 7 ppb for all hours of the year. This may be a unique aspect of very energy efficient homes. While a reduction of only 1 ^oC from 24.4 to 23.4 ^oC (76 to 74 ^oF) will not achieve the lowest REL at the minimum ASHRAE 62.2-2016 mechanical ventilation rate, it is a simple energy and cost effective step to reduce C_{HCHO} while simultaneously increasing indoor thermal comfort during the summer.

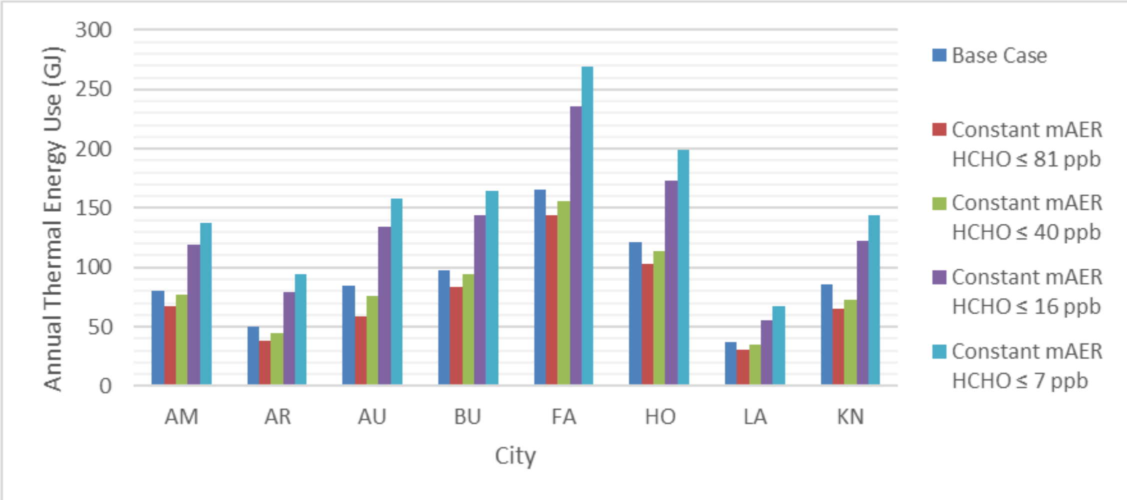


Figure 8.5: WC-2 T_{clg}=23.4C – Th. Energy Use – C mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

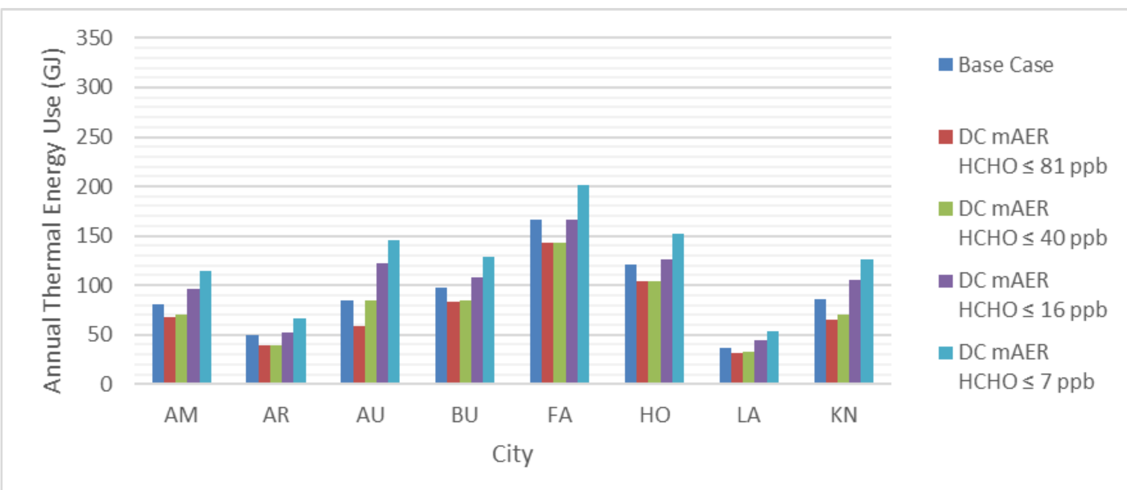


Figure 8.6: WC-2 T_{clg}=23.4C– Th. Energy Use – DC mAER for Desired HCHO REL, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

As shown in Figure 8.7, for the requirement that $C_{HCHO,i,n} \leq 40$, 16 and 7 ppb, lowering T_{Clg} by 1 ^{o}C (from 24.4 to 23.4 ^{o}C / 76 to 74 ^{o}F) reduced annual energy consumption by an average of ~10% across all climate zones for constant mAER. For the base case (ASHRAE minimum required mAER) and for $C_{HCHO,i,n} \leq 81$ ppb, energy use increased.

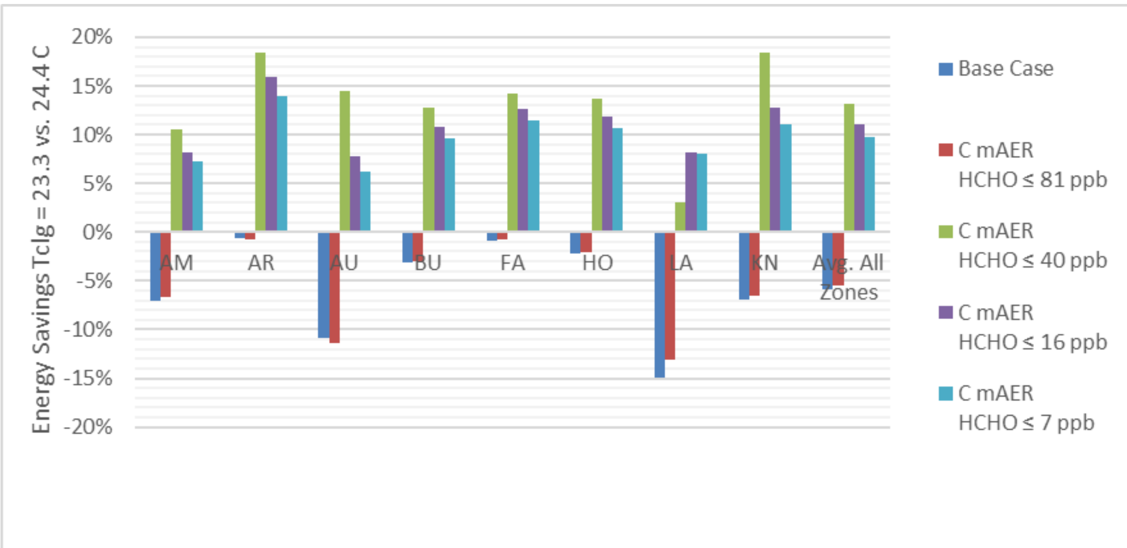


Figure 8.7: % Energy Savings from Reducing T_{clg} 1 ^{o}C – C mAER, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

When DC ventilation is used, there is only a 1-3% reduction in annual energy use when T_{clg} is reduced 1 ^{o}C and then only for $C_{HCHO,i,n} \leq 40$, 16 and 7 ppb in some climate zones as shown in Figure 8.8.

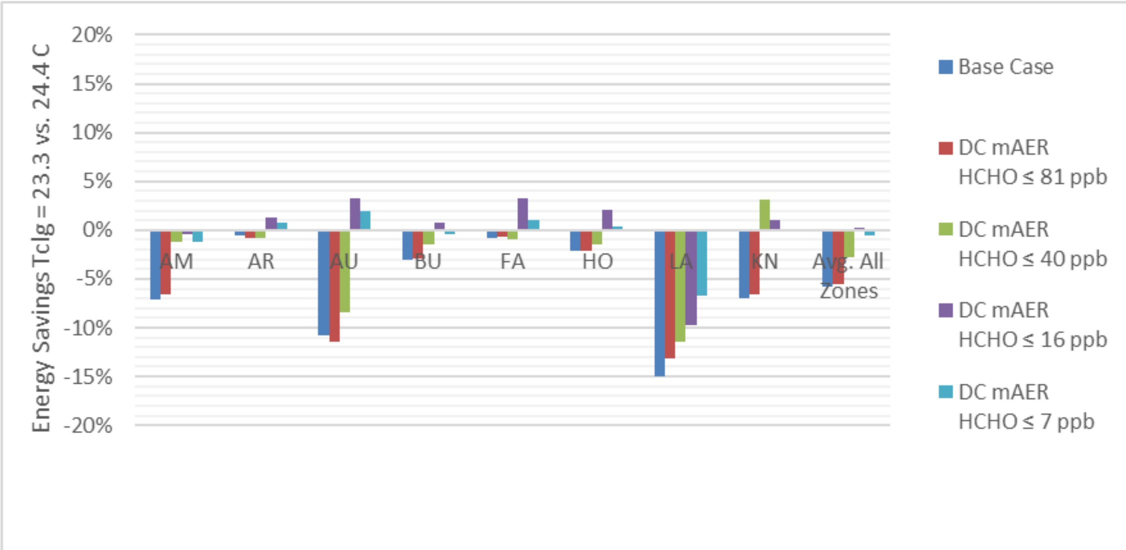


Figure 8.8: % Energy Savings from Reducing T_{clg} 1 °C – DC mAER, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

8.3 Constant Mechanical Ventilation and Improved Superposition

Four constant mechanical ventilation rates were studied to compare the use of superposition of infiltration and mechanical ventilation using quadrature and the improved superposition calculation proposed by Hurel et al. (2015) described in Section 6.3.2. Results are shown in Figure 8.9. Comparisons were made for house WC-2 in Austin, TX.

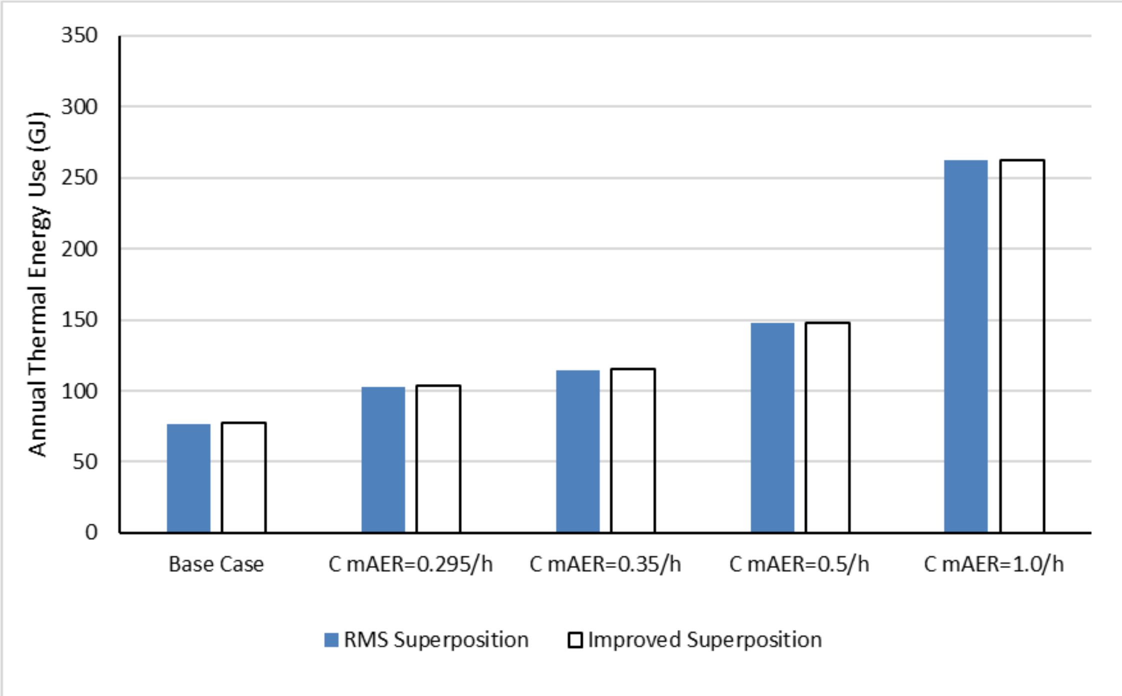


Figure 8.9: Constant mAER – Impact of Improved Superposition

The percent difference between these two superposition approaches for House WC-2 in Austin was < 1%, which is below the accuracy of the FREE model. This is expected based on the findings of Hurel et al. (2015), who found that quadrature gave good predictions for tight homes (α < 0.4). The low annual average infiltration rate (0.045 h^{-1}) leads to low (0.27 to 0.045) infiltration factors (α) for this house in Austin. The infiltration factors were calculated as shown in Section 6.3.2. Details of the infiltration factors can be found in Appendix Table H.28.

8.4 Exploratory Scenarios

Exploratory scenarios to evaluate the energy impact of: 1. Lower HCHO emission rates (ER_{HCHO}), 2. Filtration of indoor air with gas phase filtration (GPF) combined with mechanical ventilation up to the ASHRAE minimum requirement, and 3. Two energy recovery ventilators (ERVs) are explored in this section.

Results for constant mAER scenarios are shown in Figure 8.10 and for demand controlled scenarios in Figure 8.11.

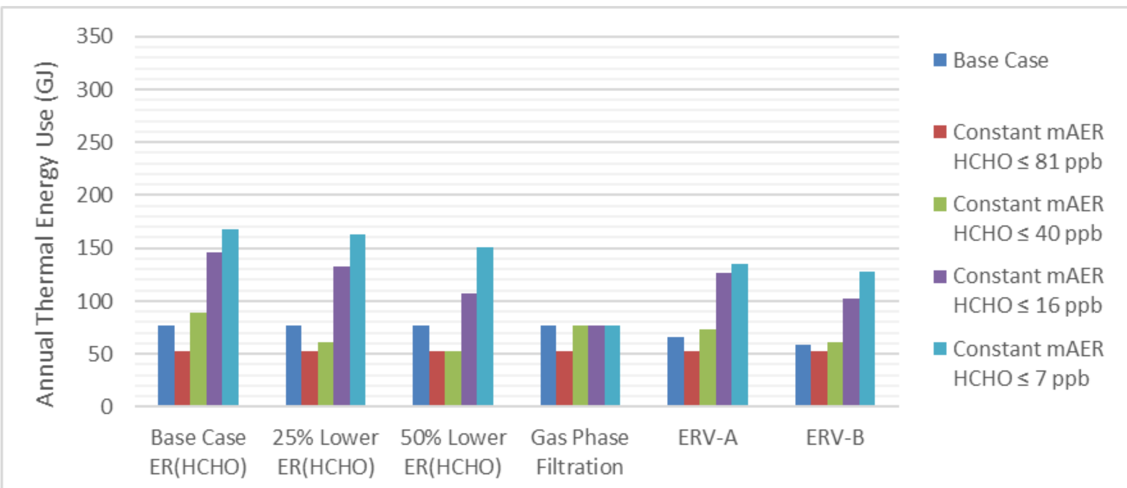


Figure 8.10: Exploratory Scenarios – Annual Thermal Energy Use – C mAER

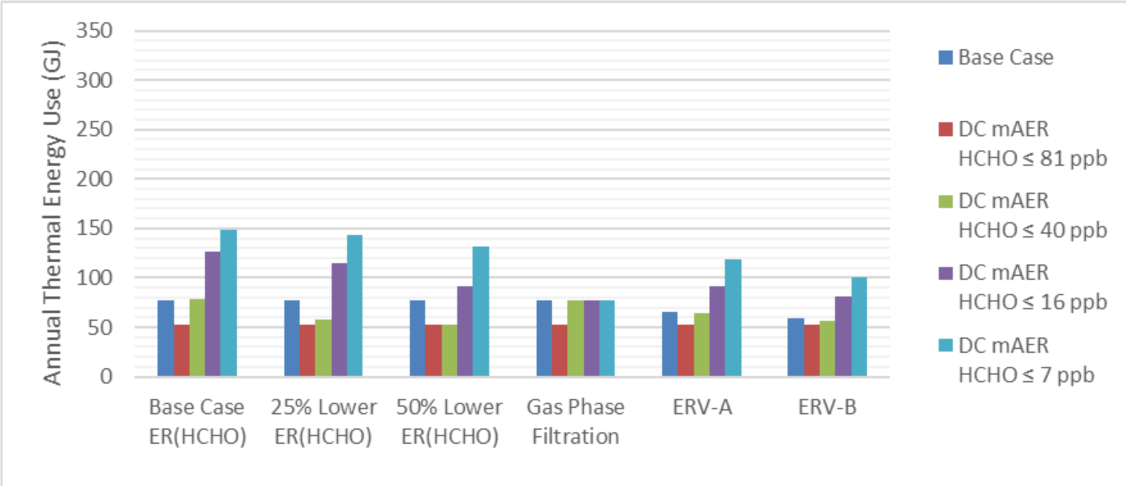


Figure 8.11: Exploratory Scenarios – Annual Thermal Energy Use – DC mAER

The energy reduction from demand controlled ventilation is not nearly as pronounced in these scenarios. In the GPF case, the same mAER is used so no change is anticipated. As the ERVs are very energy efficient, they do not show the same reduction in energy when going from C mAER to DC mAER – the energy savings are already apparent in the C mAER scenarios.

8.5 Sensitivity Analysis of Elevated $C_{HCHO,o}$

A sensitivity analysis was conducted for Los Angeles (LA) to estimate the impact of higher outdoor concentrations of HCHO ($C_{HCHO,o}$). The energy use for constant mAER is shown in Figure 8.12 and for demand controlled mAER in Figure 8.13.

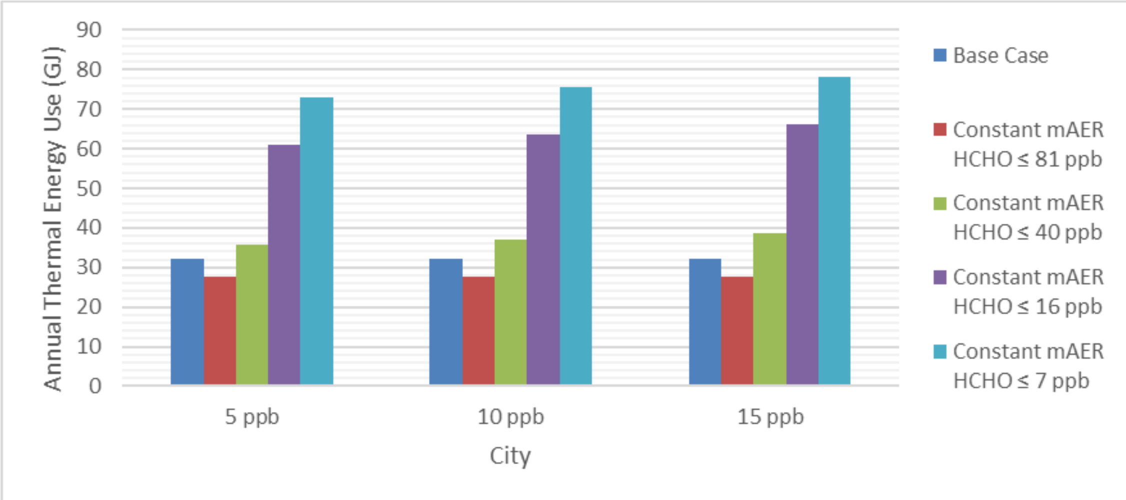


Figure 8.12: LA- $C_{HCHO,o}$ Scenarios – Ann. Th. Energy Use – C mAER

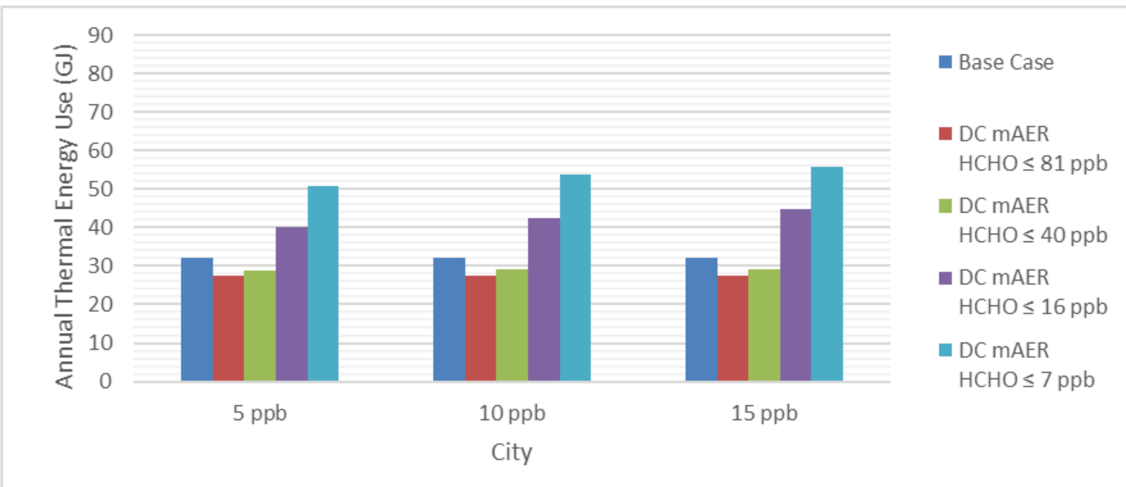


Figure 8.13: LA- $C_{HCHO,o}$ Scenarios – Ann. Th. Energy Use – C mAER

There is an ~10% increase in energy use between 5 ppb and 15 ppb. This is moderated by:

- the fact that LA is a fairly temperate climate (lowest total degree days of all cities studied – see Table 6.7)

- in the system studied, the outdoor air is filtered through a GPF system so that all mechanically ventilated air is subject to a carbon/chemisorption filter with 60% HCHO remove efficiency as shown in Figure 6.2 previously.
- the assumption that $C_{HCHO,o}$ was constant year round.

When $C_{HCHO,o}$ exceeds the desired indoor concentration, GPF in addition to ventilation will be required to achieve the desired concentration.

8.6 Fan Energy

A separate model analysis was performed to evaluate the proportion of total energy due to fans used to move ventilation air or that used in GFP. Table 8.1 shows the percent of electricity used by the fan in house WC-2 in each of the eight climate zones studied when a HEPA/carbon filter was used to filter all incoming air. It can be seen that the % of energy required increases as the C_{HCHO} is decreased. Further, the least % of energy for fan use is in harsh environments (Fairbanks, Houghton, and Buffalo) and the highest % of energy is used in mild environents (Los Angeles and Arcata). Demand controlled ventilation reduced the % of energy used for fans relative to constant ventilation, as would be expected due to less fan use.

Table 8.1: Percent of Electrical use by Fan, WC-2, Ventilation with HEPA/Carbon Filter

Location (Climate Zone) $T_{Clg} = 24.4\,^{o}C$	Percent of Electrical Use by Fan, %								
	Base Case ASHRAE 62.2-2016 Min	$C_{HCHO} \le 81$ ppb		$C_{HCHO} \le 40$ ppb		$C_{HCHO} \le 16$ ppb		$C_{HCHO} \le 7$ ppb	
	Constant mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER
Amarillo, TX (Mixed-Dry)	10%	0%	0%	13%	6%	18%	16%	19%	18%
Arcata, CA (Marine)	15%	0%	0%	17%	0%	22%	17%	23%	20%
Austin, TX (Hot-Humid)	12%	0%	0%	14%	9%	18%	16%	19%	17%
Buffalo, NY (Cold)	8%	0%	0%	11%	3%	15%	12%	16%	14%
Fairbanks, AK (Sub -Artic)	5%	0%	0%	6%	1%	9%	7%	10%	8%
Houghton, MI (Very Cold)	7%	0%	0%	8%	1%	12%	9%	13%	11%
Los Angeles, CA (Hot-Dry)	24%	0%	0%	28%	12%	33%	32%	33%	33%
Knoxville, TN (Mixed-Humid)	11%	0%	0%	13%	6%	17%	15%	18%	16%
Avg. over all sites:	12%	0%	0%	14%	5%	18%	15%	19%	17%

Table 8.2 shows that when no HEPA/Carbon filter is used and an in-line fan meeting the IECC (2015) efficacy requirements is used, substantially less energy is used for moving ventilation air.

Table 8.2: Percent of Electrical use by Fan, WC-2, Ventilation with IECC (2015) in-line Fan, No HEPA/Carbon Filter

Location (Climate Zone) T_{Clg} = 24.4 °C	Percent of Electrical Use by Fan, %								
	Base Case ASHRAE 62.2-2016 Min	$C_{HCHO} \leq 81$ ppb		$C_{HCHO} \leq 40$ ppb		$C_{HCHO} \leq 16$ ppb		$C_{HCHO} \leq 7$ ppb	
	Constant mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER	Constant mAER	Demand Controlled mAER
Amarillo, TX (Mixed-Dry)	10%	0%	0%	9%	4%	12%	10%	13%	12%
Arcata, CA (Marine)	15%	0%	0%	11%	0%	15%	11%	15%	13%
Austin, TX (Hot-Humid)	12%	0%	0%	9%	6%	12%	10%	12%	11%
Buffalo, NY (Cold)	8%	0%	0%	7%	2%	10%	8%	10%	9%
Fairbanks, AK (Sub -Artic)	5%	0%	0%	4%	0%	6%	4%	6%	5%
Houghton, MI (Very Cold)	7%	0%	0%	5%	1%	8%	6%	8%	7%
Los Angeles, CA (Hot-Dry)	24%	0%	0%	19%	8%	23%	22%	23%	23%
Knoxville, TN (Mixed-Humid)	11%	0%	0%	8%	4%	11%	9%	12%	11%
Avg. over all sites:	12%	0%	0%	9%	3%	12%	10%	12%	11%

For ERV-A, fan energy for filtration of all the outdoor mechanical ventilation air through the HEPA/Carbon filter is ~21% and fan energy for moving the air through ERV-A is ~6% of the total electrical energy required to achieve $C_{HCHO} \leq 16$ ppb in house WC-2 in Austin using constant mAER. The amount of energy used by the ERV is small in comparison to the amount of energy used to filter all the outdoor mechanical ventilation air through the HEPA/Carbon filter and verifies the assumption that the contribution of the ERV fan is small. In equipment that would actually be used in a residential installation, the HEPA/Carbon (or high efficiency particulate filter) would be included in the ERV and thus a separate HEPA/Carbon filter (and thus a separate fan) would not be used. Details of the fan energy calculation are provided in Appendix I, Table I.66.

8.7 HCHO Emission Rates

The correlations for C_{HCHO} shown in Eqn. 6.4 for house WC-2 were used to calculated $C_{HCHO,i}$ for each hour of the year in FREE using infiltration rates obtained from EnergyPlus™ and mAER used in the FREE program. Whole-house emission rates of formaldehyde for houses WC-2 and WC-3 were estimated each hour of the year in FREE in the eight climate zones for House WC-2 at T_{Clg} = 24.4 and 23.4 ^{o}C and House WC-3 at T_{Clg} = 24.4 ^{o}C using Eqn. 8.1. While emission rates could have been obtained from EnergyPlus™, it was computationally more expedient to obtain them from the FREE model using the infiltration data from EnergyPlus™.

$$ER_{HCHO} = \frac{\lambda_{tot}(C_{HCHO,i} - C_{HCHO,o})V}{A} \tag{8.1}$$

where,

ER_{HCHO} = emission rate, μg/(m^2 h)
λ_{tot} = air exchange rate, h^{-1}
$C_{HCHO,i}$ = indoor concentration of HCHO, μg/m^3
$C_{HCHO,o}$ = outdoor concentration of HCHO, μg/m^3
V = volume of house, m^3
A = floor area of house, m^2

Annual average emission rates are shown in Figure 8.14. The whiskers represent the minimum and maximum hourly emission rates in the year.

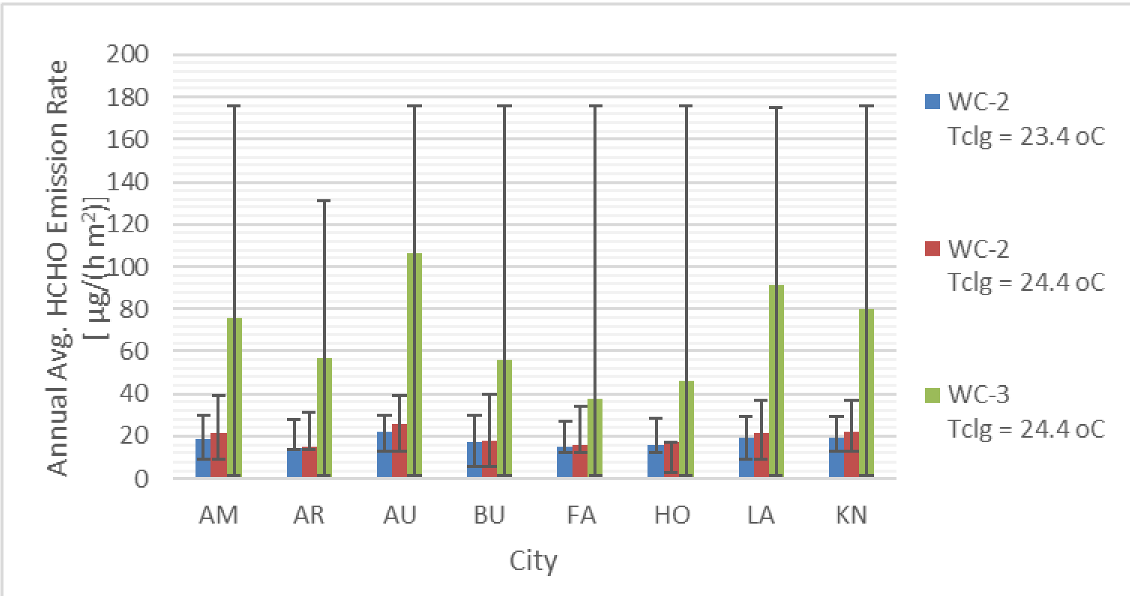


Figure 8.14: Ann. Avg. HCHO Emission Rate (whiskers are hourly Min/Max ER), AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

The emission rates shown in Figure 8.14 can be compared to the emission rate categories (Low/Med/High) reported by Turner (Ref) as 9.7/30.8/88.2 µg/(h m^2) respectively as reported previously in Table 2.6. House WC-2 is in Turner's Low to Med categories while house WC-3 is in the Med to High categories

8.8 Energy Metrics

The six energy metrics described in Chapter 7 are summarized below for easy reference. For detailed descriptions, refer to Chapter 7.

Energy Metrics:

1. Area Based Annual Energy Consumption, $AEC_{A,HCHO=REL\ in\ ppb}$
2. Volume Based Annual Energy Consumption, $AEC_{V,HCHO=REL\ in\ ppb}$
3. Area Based Annual Energy Consumption using TDD, $AEC_{A,HCHO=REL\ in\ ppb,\ TDD18.3}$
4. Volume Based Annual Energy Consumption using TDD, $AEC_{V,HCHO=REL\ in\ ppb,\ TDD18.3}$
5. Normalized λ_{mAER} Normalized to $\lambda_{ASHRAE\ 62.2\text{-}2016,\ mAER}$ to Achieve Desired HCHO RELs, $\lambda_{Ann,n,HCHO=REL\ in\ ppb}$
6. Energy Consumption Normalized to FEMA Base Case (C mAER ≤16 ppb), $AEC_{A,HCHO=REL\ in\ ppb,\ FEMA}$

These six metrics for house design WC-2 in Austin are shown below as follows:

- Table 8.3: C mAER
- Table 8.4: DC mAER
- Table 8.5: GPH with C mAER through GPF + up to ASHRAE min mAER C mAER of ventilation air
- Table 8.6: GPH with DC mAER through GPH + up to ASHEAE min mAER C mAER of ventilation air

Table 8.3: Energy Metrics for C mAER – WC-2/AU

Energy Metric	Units	Base Case	Constant mAER HCHO ≤ 81 ppb	Constant mAER HCHO ≤ 40 ppb	Constant mAER HCHO ≤ 16 ppb	Constant mAER HCHO ≤ 7 ppb
$AEC_{A,HCHO}$	$MJ/m^2/y$	222	152	257	423	488
$AEC_{V,HCHO}$	$MJ/m^3/y$	60	41	69	114	131
$AEC_{A,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.048	0.033	0.056	0.091	0.105
$AEC_{V,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.013	0.009	0.015	0.025	0.028
λann,n,HCHO	unitless	1.00	0.00	1.36	2.96	3.57
$AEC_{A,HCHO,FEMA}$	unitless	0.53	0.36	0.61	1.00	1.15

Table 8.4: Energy Metrics for DC mAER – WC-2/AU

Energy Metric	Units	Base Case	DC mAER HCHO ≤ 81 ppb	DC mAER HCHO ≤ 40 ppb	DC mAER HCHO ≤ 16 ppb	DC mAER HCHO ≤ 7 ppb
$AEC_{A,HCHO}$	$MJ/m^2/y$	222	152	227	368	431
$AEC_{V,HCHO}$	$MJ/m^3/y$	60	41	61	99	116
$AEC_{A,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.048	0.033	0.049	0.079	0.093
$AEC_{V,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.013	0.009	0.013	0.021	0.025
λann,n,HCHO	unitless	1.00	0.00	0.73	2.23	2.83
$AEC_{A,HCHO,FEMA}$	unitless	0.53	0.36	0.54	0.87	1.02

The energy metrics shown in Tables 8.3 and 8.4 show that to achieve the NIOSH/FEMA REL for HCHO (16 ppb), which is required for manufactured housing, in house WC-2 required approximately three times the base case C mAER rate and 1.9x the energy use. For demand controlled ventilation, an annual average of approximately 2.2x the ventilation is required and 1.7x the energy use as the base case.

Table 8.5: Energy Metrics for GPF with C mAER through GPF+up to ASHRAE min C mAER of ventilation air – WC-2/AU

Energy Metric	Units	Base Case	Constant mAER HCHO ≤ 81 ppb	Constant mAER HCHO ≤ 40 ppb	Constant mAER HCHO ≤ 16 ppb	Constant mAER HCHO ≤ 7 ppb
$AEC_{A,HCHO}$	$MJ/m^2/y$	222	152	222	222	222
$AEC_{V,HCHO}$	$MJ/m^3/y$	60	41	60	60	60
$AEC_{A,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.048	0.033	0.048	0.048	0.048
$AEC_{V,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.013	0.009	0.013	0.013	0.013
λann,n,HCHO	unitless	1.00	0.00	1.00	1.00	1.00
$AEC_{A,HCHO,FEMA}$	unitless	1.00	0.69	1.00	1.00	1.00

Table 8.6: Energy Metrics for GPF with DC mAER through GPF + up to ASHRAE min C mAER of ventilation air – WC-2/AU

Energy Metric	Units	Base Case	DC mAER HCHO ≤ 81 ppb	DC mAER HCHO ≤ 40 ppb	DC mAER HCHO ≤ 16 ppb	DC mAER HCHO ≤ 7 ppb
$AEC_{A,HCHO}$	$MJ/m^2/y$	222	152	222	222	222
$AEC_{V,HCHO}$	$MJ/m^3/y$	60	41	60	60	60
$AEC_{A,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.048	0.033	0.048	0.048	0.048
$AEC_{V,HCHO,TDD18.3}$	$MJ/m^3/$ TDD18.3/y	0.013	0.009	0.013	0.013	0.013
λann,n,HCHO	unitless	1.00	0.00	1.00	1.00	1.00
$AEC_{A,HCHO,FEMA}$	unitless	1.00	0.69	1.00	1.00	1.00

The results reported in Table 8.5 for C mAER and Table 8.6 for DC mAER are identical since the demand control is on the GPF which does not vary the outdoor air ventilation rate. Only thermal energy is considered here. Fan energy for the air handler, but not ventilation air through the HEPA/carbon filter or for GPF, is included when the total energy cost including the Societal Cost of Carbon is reported after converting thermal energy to electrical energy by dividing by the annual average coefficient of performance (COP) shown in Appendix H in Table H.6.

Tables 8.5 and 8.6 show that no additional thermal energy is required to achieve the NIOSH/FEMA REL. GPH in combination with constant and potentially demand controlled mAER may prove to be an energy and cost efficient way of optimizing IAQ and energy use. To achieve this goal, manufacturers will need to find ways to produce GPF devices cost effectively and with low-cost annual replacement filters or long-life catalysts that do not produce intermediates and are not deactivated by contaminants commonly found in homes. One promising approach is that of Sidheswaran et al. (2011), which uses MnOx as a room temperature catalyst for formaldehyde.

8.9 Practical Implications

Questions from an energy policy analyst, ASHRAE 62.2 committee member, and HVAC equipment manufacturer or builder's perspectives should be:

> #1 "What is the overall energy cost of additional ventilation to achieve a specific $C_{HCHO,i}$ by increasing the ventilation rate above ASHRAE 62.2-2016 minimum required ventilation rates?"
>
> #2 "What is the optimal concentration of formaldehyde when all energy and health risk costs are included?"
>
> #3 What is the potential value of equipment upgrades based on energy savings?

These practical questions are addressed in sub-sections 8.9.1, 8.9.2, and 8.9.3 below. The discussion is limited to the House WC-2 design using T_{Clg} = 24.4 °C. It should be <u>very clear</u> that the following is based only on a single house with relatively low HCHO emission rates. No generalizations can be made until a significant number of homes have been evaluated using this approach.

8.9.1 Additional Energy Cost of Achieving Specified $C_{HCHO,i}$

There are multiple reference exposure limits (RELs) promulgated by various health and government agencies. I have considered RELs for $C_{HCHO} \leq$ 81, 40, 16, 7 ppb, which are RELs suggested by WHO, Health Canada, NIOSH/FEMA, and CA OEHHA respectively, as discussed in Chapter 2.

In this study, I analyzed the site-specific energy cost, including the societal cost of carbon (SCC) in Chapter 7, and applied that to the additional electricity required, calculated by the FREE program described in Chapter 6. The additional energy cost varies by location as well as desired C_{HCHO} as shown in Figure 8.15.

Figure 8.15: Add. Energy Cost + SCC to Achieve Desired C_{HCHO} ($/y) – C mAER, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

For a single, unique house design, WC-2, using data collected in one location and extensive modeling for the other seven climate zones, to achieve the WHO 81 ppb REL, less ventilation is required and energy savings of $170 - $450/year can be obtained by reducing the ventilation rate. To achieve Health Canada's 40 ppb REL, an additional $80 - $320/year is required. For the NIOSH/FEMA 16 ppb REL, an additional $550 - $1,900/year is required. For the CA OEHHA 7 ppb REL, an additional $750 - $2,500/year is required.

Use of demand controlled ventilation significantly reduces the additional energy cost required as shown in Figure 8.16.

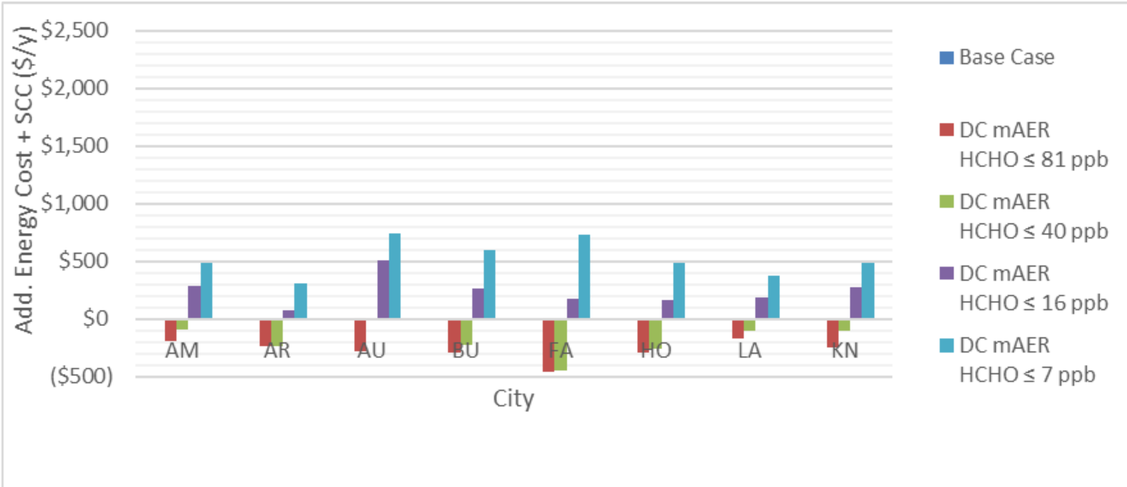


Figure 8.16 Add. Energy Cost + SCC to Achieve Desired C_{HCHO} ($/y) – DC mAER, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

The difference in the additional energy cost plus the SCC between the C mAER and DC mAER is an estimate of the value of a real-time formaldehyde monitor including installation costs such as that described in Chapter 9. The estimated value of the real-time monitor ranges from $0 if the desired REL for HCHO is 81 ppb, $140 - $760/y if the desired REL for HCHO is 40 ppb, and $220 - $1,700 for both the 16 and 7 ppb REL cases as shown in Figure 8.14. The value is far greater in extreme heating climates including the Sub-Artic, Very Cold and Cold climate zones than in more temperate climate zones.

If a general correlation exists between T_{in} and C_{HCHO} such as increasing λ_{tot} by 0.1 h^{-1} is approximately equivalent to reducing the indoor temperature by 1 K in terms of reduction of C_{HCHO} discussed in section 5.1, a simple ventilation controller based only on T_{in} may be possible. Clearly the paucity of data from only three homes precludes any generalization. However, it does suggest that this may be worth considering further as data are collected from large field studies currently being planned by the U.S. DOE in 100+ homes.

8.9.2 Optimal Concentration of Formaldehyde

Determining the cost of achieving a specified C_{HCHO} using only the cost of energy and the Societal Cost of Carbon as done in Section 8.8.1 is short-sighted and leads to the conclusion that the highest C_{HCHO} REL studied (81 ppb) is the optimal concentration. Unfortunately, exposure to this concentration over a life-time may lead to a 1 in 1000 to 1 in 100 risk of cancer as discussed in Chapter 2. Such cancer risks are up to three orders of magnitude higher than the 1 in 100,000 cancer risk typically acceptable for the general U.S. public as discussed in Chapter 2.

From a pragmatic perspective, if a governmental regulatory body requires achieving a specific C_{HCHO}, even if not optimal, that is likely the concentration that will be adopted. In the U.S., currently, only manufactured housing is required to achieve a specified C_{HCHO}, the NIOSH/FEMA REL of 16 ppb, as discussed in Chapter 2.

An alternative approach to finding an optimal C_{HCHO} is to monetize the health impacts of exposure to formaldehyde using the DALYs approach described in Chapter 3 and add those to the cost of energy and SCC to determine an annual Non-Capital Cost (NCC_{ann}) as shown in Eq. 8.2.

$$NCC_{ann,CI} = Elec\$_{ann} + SCC_{ann} + \$DALYs_{ann,CI} \tag{8.2}$$

where,

subscripts:

- $_{ann}$ = annual
- $_{CI}$ = Confidence interval of $DALYs
  - $_{Med}$ = Median value of $DALYs
  - $_{68\%}$ = 68% Upper CI of $DALYs
  - $_{95\%}$ = 95% Upper CI of $DALYs

NCC_{ann} = Annual Non-Capital Cost, $/y
$Elec\$_{ann}$ = Annual Cost of Electricity used at the specific site, $/y
SCC_{ann} = Annual Associated Societal Cost of Carbon, $/y

The C_{HCHO} that provides the minimum NCC_{ann} for the given house in the given climate zone is the optimal C_{HCHO}. The optimal C_{HCHO} for WC-2 in all eight climate zones for the Median, 68% and 95% DALY confidence levels is shown in Appendix H, Table H.5 and H.6 for C mAER and DC mAER at T_{clg} = 24.4 °C respectively. This information is shown graphically in Figures 8.17 and 8.18 which show that use of demand controlled (DC) mechanical ventilation (mAER) reduces the optimal C_{HCHO}.

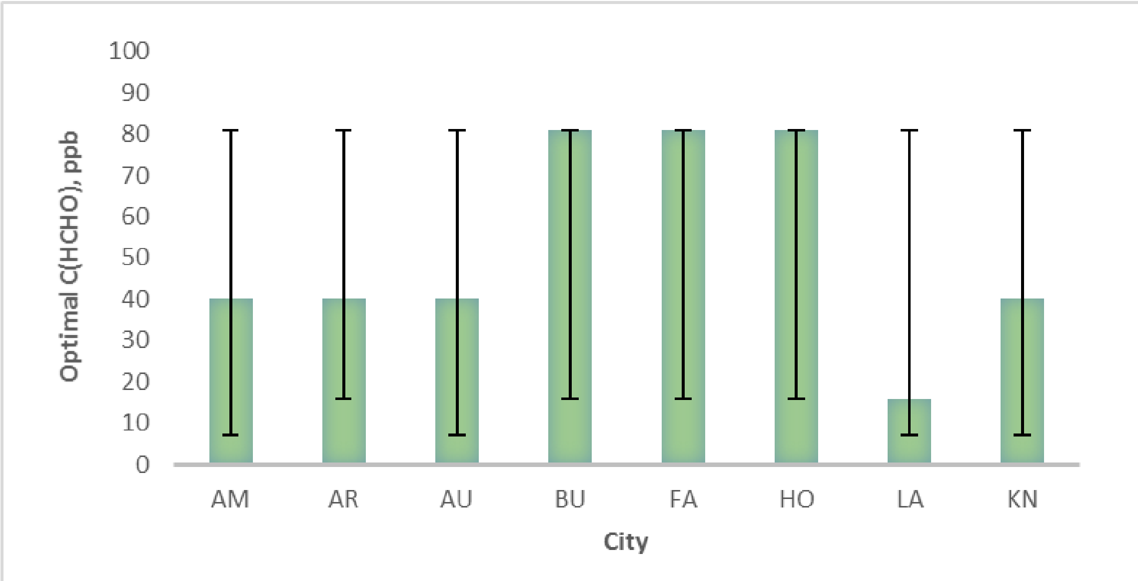


Figure 8.17: Optimal C_{HCHO}: WC-2/CmAER/24.4C $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

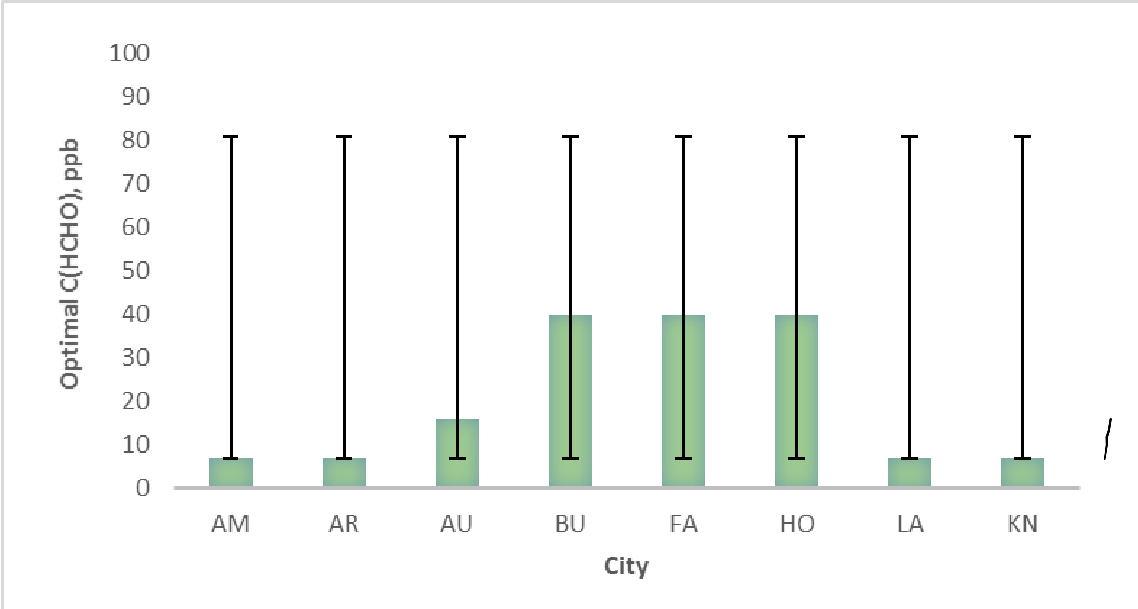


Figure 8.18: Optimal C_{HCHO}: WC-2/DCmAER/24.4C $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

The optimal C_{HCHO} for WC-2 in all eight climate zones for C mAER and DC mAER at T_{clg} = 23.4 °C are shown in Figures 8.19 and 8.20 for respectively. Again, demand controlled ventilation provides lower optimal C_{HCHO}.

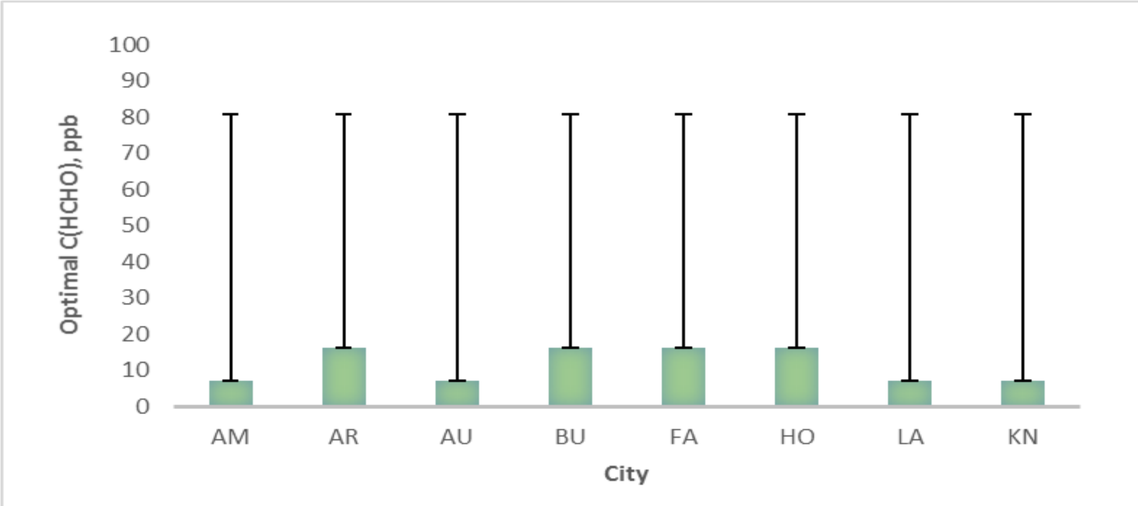


Figure 8.19: Optimal C_{HCHO}:WC-2/CmAER/23.4 ºC $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

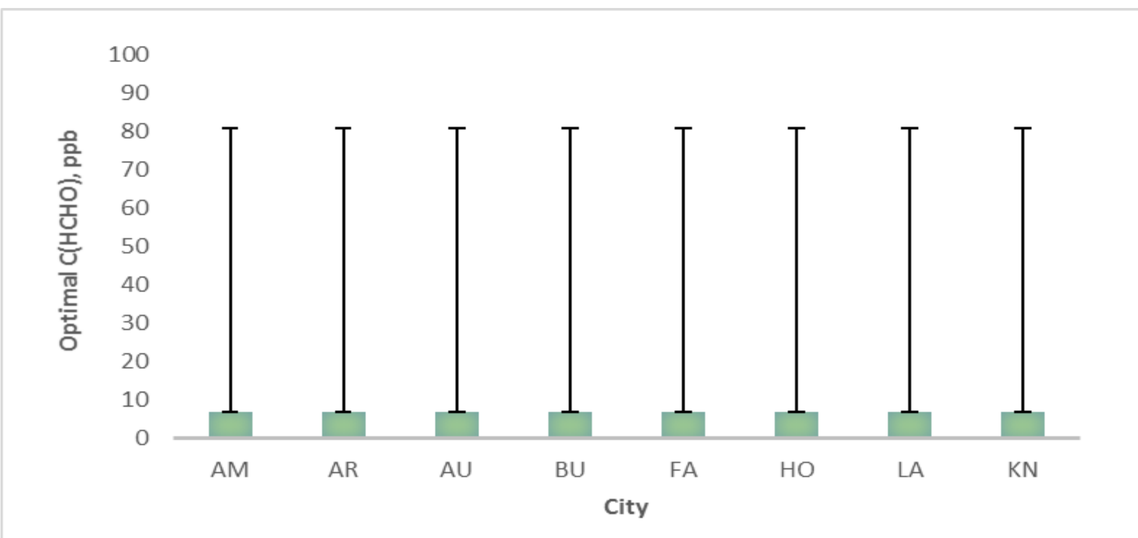


Figure 8.20: Optimal C_{HCHO}:WC-2/DCmAER/23.4 ºC $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

The optimal C_{HCHO} for WC-3 in all eight climate zones for C mAER and DC mAER at T_{clg} = 24.4 ^{o}C are shown in Figures 8.21 and 8.22 for respectively. Due to the very high emission rates observed in this house design, in Fairbanks and Houghton, the optimal C_{HCHO} is very high. The high concentration is the maximum found when ASHRAE 62.2-2016 minimum required ventilation is used – C_{HCHO} in every hour of the year are less than or equal to the given concentration. This is somewhat of an artifact as constant ventilation was used all year long at the rate that reduced the C_{HCHO} during the maximum emission rate. Thus, in these very cold climates, significant amounts of cold air are brought in during the winter time that are really only needed during the summer time when cooling is used (for only a few hours a year in these climate zones). The impact of demand controlled ventilation is particularly striking in house WC-3, especially in the cold climate zones.

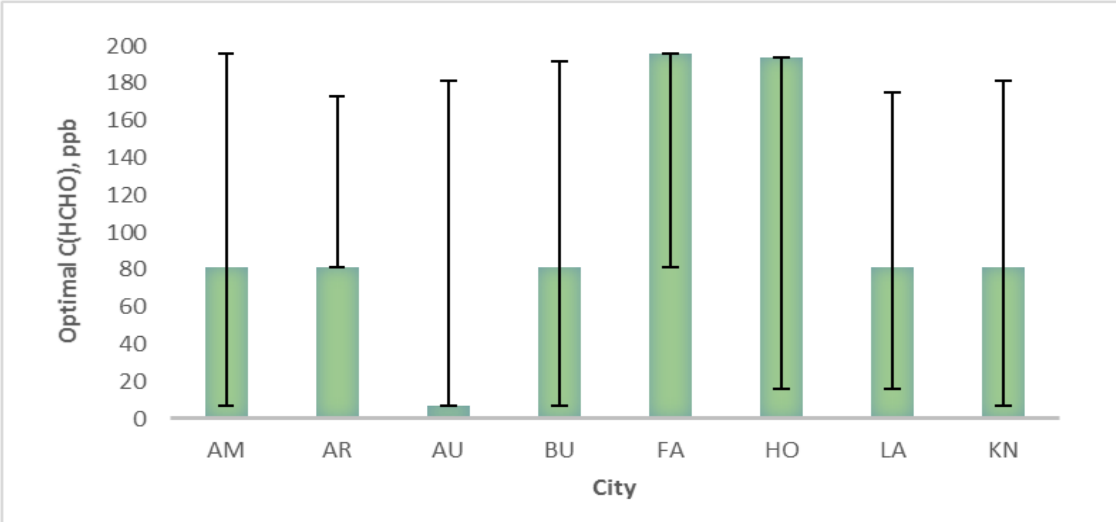


Figure 8.21: Opt. C_{HCHO}: WC-3/CmAER/24.4C $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

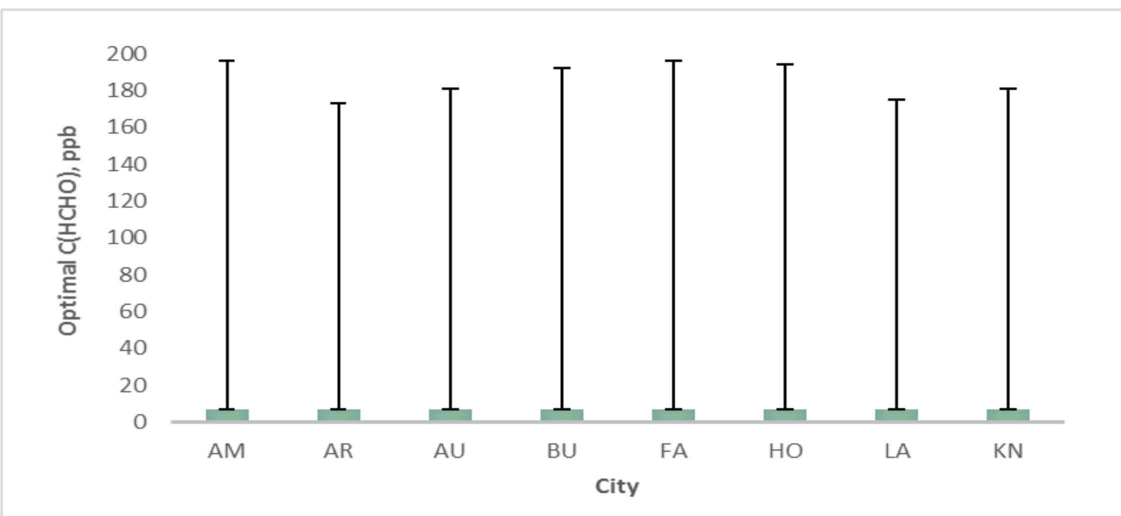


Figure 8.22: Opt. C_{HCHO}: WC-3/DCmAER/24.4C $NCC_{68\%}$-whiskers Med/95%, ppb, AM = Amarillo; AR = Arcata; AU = Austin; BU = Buffalo; FA = Fairbanks; HO = Houghton; LA = Los Angeles; KN = Knoxville

Limitations of this approach are primarily related to the uncertainly of DALYs lost, which is the dominant factor in determining the optimal C_{HCHO}. An additional limitation is that the capital cost of equipment, installation and maintenance is not included in this analysis. The next section provides estimates of the value of equipment upgrades.

8.9.3 Potential Value of Equipment Upgrades Based on Energy, SCC and DALYs

The potential value, based on energy savings, including SCC, of equipment upgrades is presented in Figure 8.23 for the scenarios explored in House WC-2 in Austin. All scenarios were evaluated using C mAER except for the HCHO Monitor which operates by creating DC mAER.

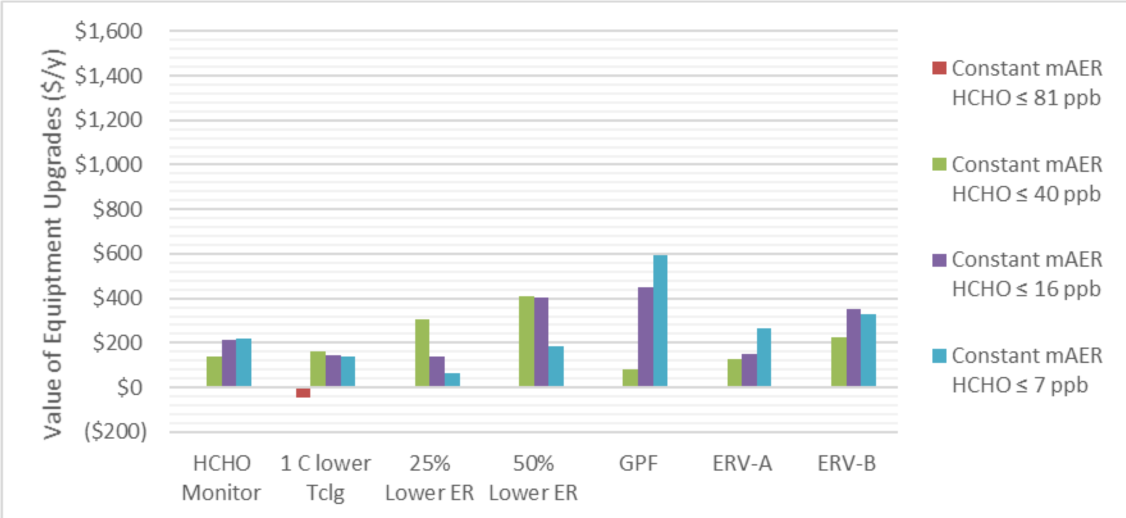


Figure 8.23: Potential Value of Equipment Upgrades based on energy savings and SCC – WC-2/AU, ($/y)

If the goal is to achieve C_{HCHO} of 40 ppb or less, for house design WC-2, in Austin, the least cost upgrade is simply turning down the existing thermostat by 1 ^{o}C in the summer/cooling season. Figure 8.7 above shows that this is more broadly applicable for house design WC-2 in all climate zones studied. This is contrary to conventional wisdom that to save energy, increasing the summer cooling temperature is desirable. The difference is that, in this case, a constraint has been applied to the C_{HCHO} allowed in the house. Less energy is used to cool this very energy efficient home than to condition the additional ventilation air required to off-set the increased HCHO emission rate from an increase in indoor temperature. While this is certainly an intriguing observation, the reader is reminded that the house design is unique, very energy efficient and may not be broadly applicable.

Source reduction, for instance selecting building materials and furnishings that have lower formaldehyde content, may be an additional low-cost approach to achieving desired RELs. With source reduction, no on-going energy is required to maintain the HCHO reductions. In addition, if the increased cost of the lower formaldehyde building materials is amortized into the mortgage, the savings would be for the life of the loan and, neglecting interest costs, the value could be as high as 15-30 times those shown in Figure 8.23.

If two to three year paybacks are acceptable, the retail value of the upgrade could be 2-3 times the annual savings shown in Figure 8.23. Of particular interest is the potential value of GPF when desired RELs are 16 ppb or less. This analysis can also be used to determine the relative value of a higher efficiency ERV. For instance at 16 ppb, ERV-B is worth ~$200 more per year, while at 40 ppb it is only worth ~$100 more per year.

The potential value of equipment upgrades based on $NCC_{68\%}$, which includes DALYs, energy savings and SCC is shown in Figure 8.24 for the scenarios explored in House WC-2 in Austin.

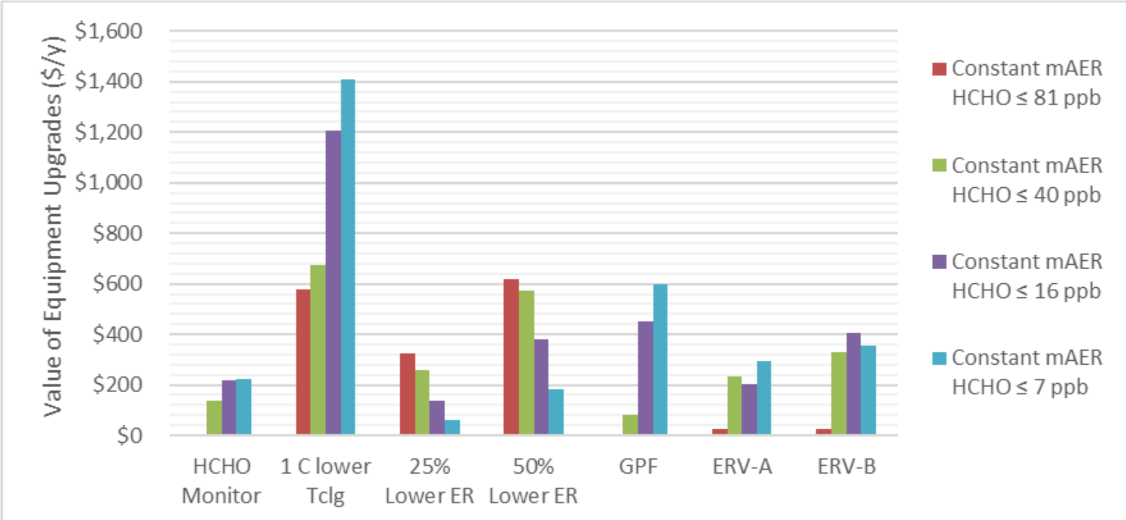


Figure 8.24: Value of Equipment Upgrades – based on $NCC_{68\%}$ - WC-2/AU, ($/y)

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The most notable outcome is the much higher value of reducing the temperature by 1 ^{o}C when NCC, which includes DALYs, energy and SCC is considered. This is due to the fact that the analysis is focused on C mAER. Reducing the temperature by 1 ^{o}C reduced the maximum emission rates significantly, which, since C mAER is based on the maximum emission rate only, allows less C mAER for the entire year.

Additional valuations based on energy and SCC as well as NCC savings are presented in Appendix H.

8.10 Summary

Chapter 8 concludes Phase 2 of this dissertation orginally shown in Figure 1.1. The ORNL field trial work described in Chapter 4 resulted in empirical models for C_{HCHO} in two homes described in Chapter 5. This work was combined with detailed modeling using the U.S.DOE' Energy Plus™ and author- developed FREE (Formaldehyde Removal and Energy Efficiency) programs described in Chpater 6 and Appendix H, and was linked with the DALY results from Chapter 3 and augmented by the fiscal bridge from energy to dollars in Chapter 7. Phase 2 of the dissertation resulted in several interesting observations:

1. Decreasing the cooling temperature set-point is a cost and energy efficient way of not only reducing the concentration of formaldehyde in the home, but increasing thermal comfort. This is contrary to conventional wisdom and may be unique to the very energy efficient homes studied.
2. Gas Phase Filtration is a potentially significant approach to efficiently achieve desired HCHO RELs – particularly the lower ones at 16 and 7 ppb. The energy saving from use of a GPF unit to achieve $C_{HCHO} \leq 7$ ppb were ~2X that achieved using an ERV, 50% reduction in the HCHO ER, reducing T_{clg} by 1 ^{o}C or use of demand controlled ventilation with a formaldehyde monitor.
3. The key parameter that determines the optimal C_{HCHO} and energy cost is the health risk associated with exposure to HCHO at concentrations in the

range of 2-81 ppb. The uncertainly of the DALY attributable to HCHO, the risk of cancer (1 in 100 to 1 in 1000 at concentrations considered in this study) and the monetary value of this health risk all need additional quantification to properly optimize energy use and C_{HCHO} in residences.

4. Inclusion of ERV fan energy may refine the analysis, but is not expected to change the overall conclusions described above.

The final portion of the dissertation, Phase 3, shown in Figure 1.1, dealing with a formaldehyde monitor to potentially provide real-time ventilation control is described in Chapter 9.

Chapter 9 Real-time Formaldehyde Monitor/Controller

As a capstone for the body of work that comprises this dissertation, a real-time formaldehyde (HCHO) monitor was explored to determine how viable such a monitor is for use as a ventilation and gas phase filtration controller.

In January 2015, the author's consulting company, McCree Consulting, LLC (MCC), acquired the rights to a formaldehyde monitor developed by DC Group International, Inc. (DCGI). The monitor was developed by the owners of DCGI (company dissolved at the end of 2014) with an investment of over $1 million to act as a ventilation controller for use in what was anticipated to be a large market in China (Russell, 2015). The DCGI HCHO monitor, developed through six generations of product refinement, was designed to provide an ON/OFF signal at 81 ppb. The author developed a seventh generation of the monitor with outside consultants with modified electronics to provide a resolution of < 1 ppb and added a temperature and relative humidity sensor. This resolution allows the full capability of the proprietary, fuel-cell based sensor, to be realized without limitations from the electronics. This chapter describes the design and construction of a novel test chamber and testing of the monitor at an outside laboratory that demonstrates a MDL of less than 16 ppb under laboratory conditions. The analyzer provides preliminary results of cross-sensitivity to the 2nd most abundant aldehyde and two most abundant alcohols identified in residential environments in Chapter 3. The ability of the 7^{th} generation HCHO monitor to theoretically measure concentrations of formaldehyde within ± 25% of the true value in residences based on the database developed in Chapter 3 is presented. On-going development work is expected to achieve a MDL of less than 5 ppb in the future.

Using the results of the modeling described in Chapters 6-8, estimates of the relative value of a HCHO monitor/controller in two homes in eight geographic locations based on energy savings are provided. These estimates are used to provide a range of cost targets for commercialization of a HCHO monitor. Whether or not these cost targets can be achieved remains to be determined in future work.

Cross-sensitivity to emissions from monitor components, aldehydes and alcohols was identified as a limiting factor in achieving a cost-effective real-time formaldehyde monitor using the current MCC technology. Future work that may address the cross-sensitivity limitation of this HCHO sensing technology is suggested.

Two in-residence tests were conducted using a calibrated MCC HCHO monitor to demonstrate “real-life” operation of the monitor. These showed a response to opening the window in one home and to operation of a printer and cycling that coincided with operation of the HVAC unit in the 2^{nd} home.

Finally, based on the potential thermal control issue identified in Chapter 5 with the colorimetric monitors, a packaging method for the MCC monitors that avoids thermal excursions was developed and demonstrated.

9.1 HCHO Sensor/Monitor Calibration:

Two monitors (#11 and #15) of the DCGI 6^{th} generation monitor were tested at the proprietary sensor manufacturer’s facility by sensor manufacturer personnel. A zero-air generator was used to provide air without any HCHO. A KinTek permeation tube oven and humidification unit, and a small glass chamber in a constant temperature bath provided the rest of the test set-up. Sensors placed inside the small glass chamber were connected to the monitor with ~1 m of hook-up wire. The initial test equipment set-up is shown in Figure 9.1.

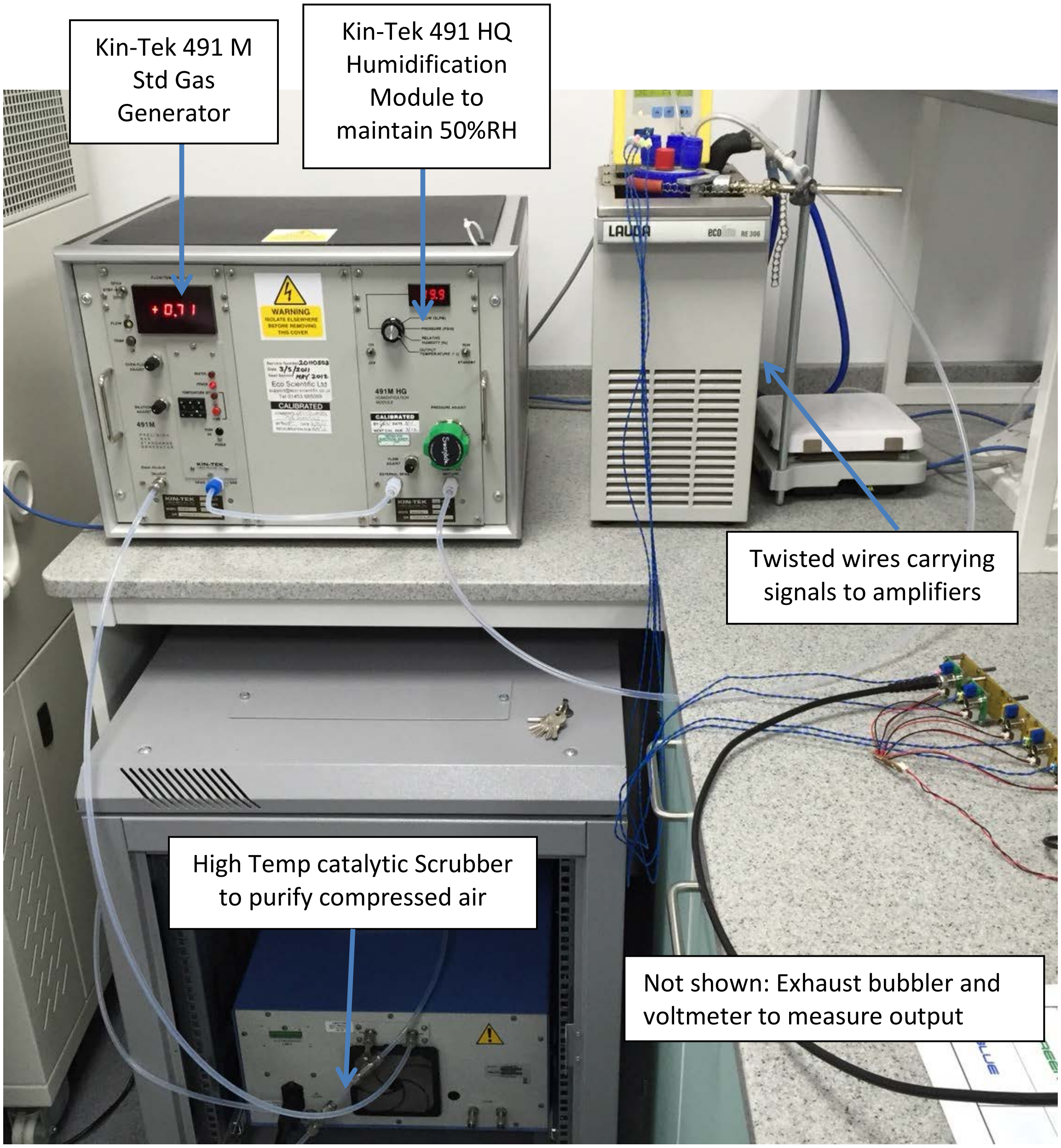


Figure 9.1: Laboratory Set-up to Calibrate HCHO Sensor.

Based on preliminary results, which measured generated C_{HCHO} at 7.3 ppb (the lowest the available permeation tube could produce), the minimum detection limit was determined to be 2 ± 6 ppb. Additional efforts have been taken to remove variation from the test measurement and improve the HCHO monitor.

Upgrades of the test equipment and HCHO monitors include:

- A customized water jacketed calibration chamber that can hold >80 sensors simultaneously. This will provide superior temperature and humidity control in addition to increasing throughput.
- A new “zero air machine” to insure that there are no detectible hydrocarbons in the zero air. This may explain a portion of the baseline drift.
- Air conditioning of the laboratory to provide more uniform thermal conditions in the lab for testing.
- Unspecified enhancements in the sensor to reduce baseline drift by the sensor manufacturer.
- Addition of a T/%RH sensor to the HCHO monitor to be able to correct for T/%RH if needed.
- Production of three 7th Generation HCHO monitors that provide better resolution at low concentration, T/%RH sensors, enhanced control capability, and hardening of the design through detailed design and manufacturability reviews.
- Improved firmware and software to allow easier calibration of sensor, T/%RH correction of C_{HCHO} and additional graphical output.

- Additional testing for cross-sensitivity of the HCHO sensor to acetaldehyde (~10% in initial testing)

Testing was performed at the author's expense so as not to utilize any university resources for development of the technology, and for convenience.

Calibration curves for two HCHO monitors are shown in Figure 9.2 and Figure 9.3. The order of testing was 0, 81, 40, 16, 7, 0 ppb in the same day. There is an approximately 6 ppb variation in the off-set.

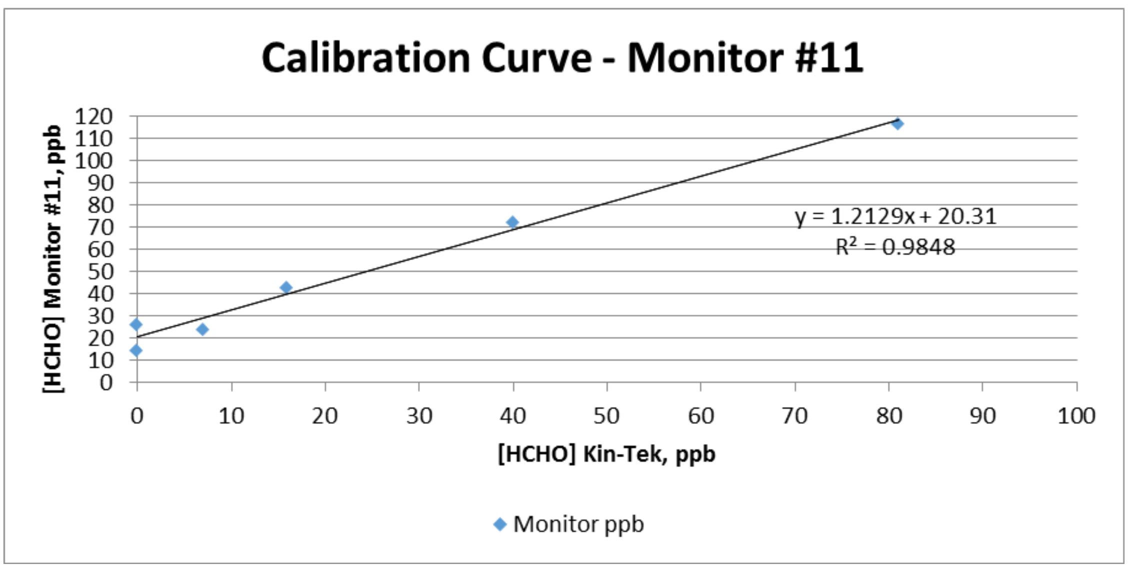


Figure 9.2**:** Calibration Curve for HCHO Monitor #11

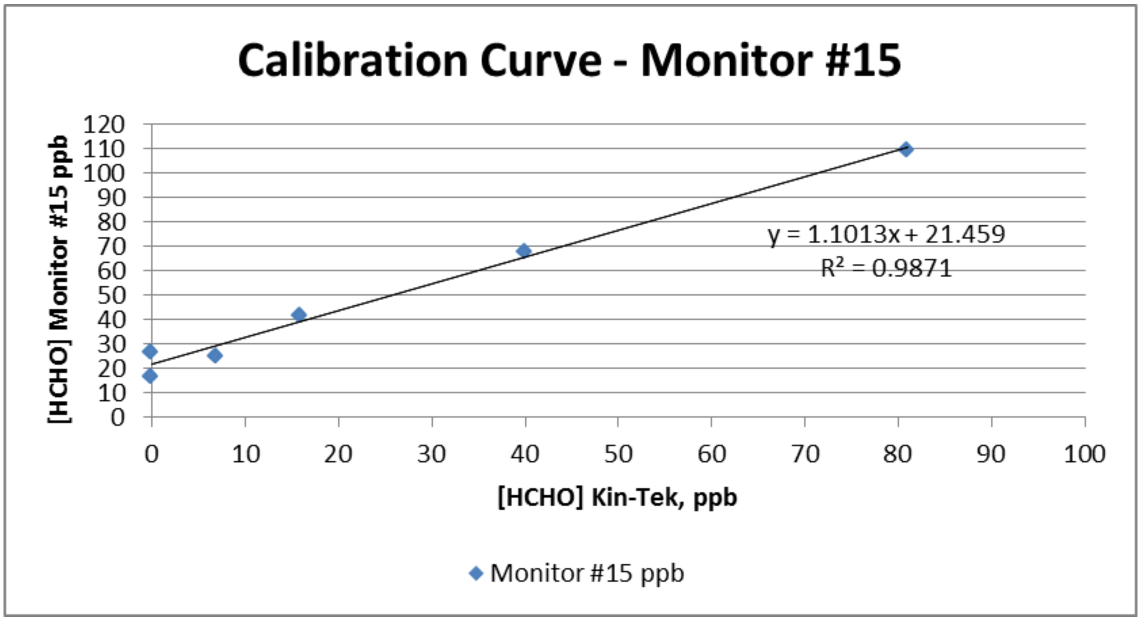


Figure 9.3: Calibration Curve for HCHO Monitor #15

The data demonstrates a 16 ppb HCHO real-time monitor with further optimization possible (i.e. more stabilization of the off-set could get to less than 7.3 ppb CA OEHHA concentration). While a concentration of 7.1 ppb was measured, a 6 ppb drift in the off-set was observed during this one-day test. With additional data, a better statistic for the correlation shown in Figure 9.3 using 95% CI of the fitted coefficients would be possible.

Such a monitor can provide a signal to turn a fan ON/OFF (0, 10 V signal to an HVAC system that will control a fan or a relay and a 12-24 V power supply to switch a 120 V motor).

To confirm the MDL and gain confidence in the design being able to provide real-time measurements at 16 ppb or lower, a larger calibration chamber was needed so that multiple sensors could be tested simultaneously and over several weeks. A custom-made glass calibration chamber, made by Eagle Laboratory Glass Company to a design that evolved between the author, the sensor manufacturer and the glass blower. An image of a completed calibration chamber is shown in Figure 9.4.

Figure 9.4: Custom Water Jacketed Calibration Chamber

A custom built five necked borosilicate cap for the calibration chamber is shown in Figure 9.5. The central neck is the exit for the calibration test gas and the four other necks are for wire bundles from the sensors to pass through to connect to monitors outside the calibration chamber.

The calibration chamber has been designed to hold up to approximately 80 sensors that can be tested simultaneously. The chamber has also been designed to hold up to 5 or 6 full monitors if desired. For full production, multiple calibration chambers could be arranged in parallel to calibrate several hundred sensors simultaneously if desired.

Figure 9.5**:** Five Necked Borosilicate Glass Cap of Calibration Chamber

9.2 Cross-Sensitivity to other household chemicals

The HCHO sensor can respond to other gases, including volatile organic compounds and inorganic gases. These will be discussed separately below.

<u>Volatile Organic Compounds</u>:

The HCHO sensor is potentially cross sensitive to other aldehydes as well as alcohols. Preliminary testing shows that the sensor has a cross-sensitivity of 45% with alcohols and 10% cross-sensitivity with acetaldehyde. Based on the technology of the sensor, it is anticipated that higher molecular weight alcohols and aldehydes will have less cross-sensitivity. However, as data are not available, a very conservative assumption was made that all higher molecular weight alcohols have the same cross-sensitivity as ethanol (methanol did not occur in the database at > 1 μg/m^3). Similarly, all higher molecular weight aldehydes were assumed to have the same cross-sensitivity as acetaldehyde.

Table 9.1 shows a summary of results obtained from analyzing all of the sampling events from the database described in Chapter 3 of the impact of these potential cross-sensitivities.

Table 9.1 Prioritizing Cross-Sensitivity Testing

	Compound	In %SEs	Assumed Cross Sensitivity							
Aldehydes (# C)	Formaldehyde (1)	100%								
	Acetaldehyde (2)	100%	10%	10%						
	Hexaldehyde (6)	94%	10%		10%					
	Valeraldehyde (5)	87%	10%			10%				
	Benzaldehyde (7)	81%	10%				10%			
	Butyraldehyde (4)	80%	10%					10%		
	Propionaldehyde (3)	71%	10%						10%	
	Nonyl Aldehyde (9)	65%	10%							10%
Alcohols (# C)	Ethanol (2)	54%	10%	45%						
	Isopropanol (8)	46%	10%		45%					
	% Samples	Worst case	35%							
	>25% above	Single Aldehydes		2%	2%	0%	0%	0%	0%	0%
	True C_{HCHO}	Single Alcohols		19%	6%	0%	0%	0%	0%	0%

Based on the data summarized in Table 9.1, priorities for further cross-sensitivity testing from alcohols and aldehydes are:

Ethanol > Isopropanol > Acetaldehyde > Hexaldehyde.

Carbon Monoxide:

The EPA has set 8-hour and 1-hour National Ambient Air Quality Standards (NAAQS) for ambient carbon monoxide concentrations (C_{CO}) at 9 ppm and 35 ppm respectively. Bell et al. (2009) report daily 1-hour maximum ambient C_{CO} from 0.2-9.7 ppm and Daily 24-hour C_{CO} of 0.05 to 2.5 ppm in their study of cardiovascular disease (CVD) hospital admissions and carbon monoxide in 126 U.S. urban counties. In their study of >9.3 million Medicare enrollees ≥ 65 years, Bell et al. (2009) report that a 1 ppm increase in 1-hour maximum C_{CO} resulted in a 0.55% increase in hospital admissions for CVD. This effect persisted at 1-hour maximum ambient C_{CO} < 1 ppm.

The sensor manufacturer reports a 1% cross-sensitivity of the HCHO sensor to carbon monoxide (CO). For typical indoor concentrations of CO of 1 ppm, this results in an uncertainty of 10 ppb in the C_{HCHO}. The U.S. Consumer Products Safety Commission CPSC (2013) requires stability testing for carbon monoxide alarms such that, to avoid “False alarms”, the alarm will not activate when C_{CO} = 30 ± 3 ppm for 30 days, or for up to 60 minutes at 70 ± 5 ppm. Thus, in a worst-case scenario, a 30 ppm C_{CO}, which would not actuate the CO alarm in the home, would read 300 ppb on the HCHO monitor.

Implications:

1. C_{CO} at concentrations which are <3% of the 1-h National Ambient Air Quality Standard (NAAQS) of 35 ppm (i.e. < 1 ppm) may increase health risks. Thus, taking action to reduce exposure to CO at concentrations less than the NAAQS may be advisable and the cross-sensitivity of the HCHO monitor to CO is an added benefit of the sensor.

2. Output of the HCHO monitor can be dominated by C_{CO} found in homes at concentrations (30 ppm) that do not trigger CO alarms and can be reported as C_{HCHO} of 97 ppb when real C_{HCHO} are 0 ppb. Thus, if homeowners are not concerned about C_{CO} more than 3 times the 24-hour NAAQS for CO of 9 ppm persisting in their home for a month, or use an unvented gas stove or other appliance in their homes, the HCHO monitor may be dominated by C_{CO} and readings may not correlate well with real C_{HCHO}.

Potential options to the CO cross-sensitivity issue are:

1. Use a low cost CO monitor using chromo-fluorogenic technology for detection of CO described by Moragues et al. (2014) and Moragues et al. (2014a) and subtract the C_{CO} from a calibrated response of the HCHO monitor,

2. Not use the HCHO monitor in homes that use natural gas or that have other combustion sources that may elevate CO (i.e. candles, cooking appliances, or unventilated attached garages)
3. Use the HCHO controller to provide maximum ventilation whenever the reading on the controller exceeds a desired setting whether the reading is elevated due to HCHO, CO, or other contaminants that the HCHO monitor is cross-sensitivity to.

Option 3 is the most conservative and health-protective option.

9.3 Determining the Efficacy of the Sensor

The database with 296 separate Sampling Episodes (SEs) was evaluated with the assumption that for the HCHO sensor, all the aldehydes were 10% cross-sensitive and the alcohols were all 45% cross-sensitive. This is a conservative assumption as it is anticipated that the higher the MW of the aldehydes and alcohols, the lower the cross-sensitivity will be.

When all 296 SEs were analyzed and cross sensitivities included, 64% of the sensor readings would be <125% of the real C_{HCHO}. The average sensor reading would be 143% > the real C_{HCHO} and the median sensor reading would be 113% > the real C_{HCHO}. Detailed statistics are shown in Table 9.2

Table 9.2: Statistics of Exceedance of Real C_{HCHO} by HCHO sensor

Min	102%
Max	845%
Avg	143%
δ	86%
CV	60%
5th %	104%
25th %	107%
50th %	113%
75th %	141%
95th %	273%

Table 9.3 shows the occurance and distribution of compounds in the database from Chapter 3 that the HCHO sensor is assumed to be cross-sensitive to.

Table 9.3: Occurrence and Distribution of Aldehydes and Alcohols in Database

Compound (#C atoms)	Occurrence, %	Median, ppb	Min, ppb	Max, ppb
Formaldehyde (1)	100%	28	2	171
Acetaldehyde (2)	100%	10	1	255
Hexaldehyde (6)	94%	2.4	0	183
Valeraldehyde (5)	87%	1.1	0	72
Butyraldehyde (4)	80%	0.9	0	29
Propionaldehyde (3)	71%	1.2	0	46
Ethanol (2)	51%	0.3	0	827
Isopropanol (8)	46%	0.0	0	116

As can be seen in Table 9.4, for each range of interest, the sensor reading, assuming 10% cross-sensitivity of all aldehydes and 45% cross-sensitivity of all alcohols with 0% cross sensitivity of all other VOCs in the database, at least 82% of the samples will read within 125% of the concentration of interest (7.3, 16, 40, 81 ppb). For the WHO concentration limit of 81 ppb, 96% of the samples with cross-sensitivities added are within 125% of the limit.

Table 9.4: Impact on Accuracy of HCHO Monitor Based on Assumed Cross-sensitivity

HCHO REL ppb	Real C_{HCHO}	# samples	125% of HCHO REL, ppb	# Samples < 125% HCHO REL (With Cross Sesitivities)	% Samples < 125% REL (With Cross Sesitivities)
7.3	0-7.3 ppb	11	9.1	9	82%
16	0-16 ppb	59	20	49	83%
40	0-40 ppb	204	50	188	92%
81	0-81 ppb	283	101	271	96%
	> 81 ppb	13			

9.4 Use of HCHO Monitor in Residences

9.4.1 Location A: Impact of opening a window

Location A is a residence with elevated C_{HCHO} and an unvented gas stove that is in the 75th percentile of C_{HCHO} in homes based on the database developed in Chapter 3 when a 24-hour air sample was collected and analyzed using the DNPH technique. HCHO monitor #11 was located in a guest room of the residence.

Figure 9.6 shows the impact of opening and closing the window on the HCHO monitor output. The carbon monoxide (CO) from the unvented natural gas combustion may be contributing to the elevated HCHO monitor readings in this residence. This residence had just added new pressed wood shelving units in several closets and the outdoor air (OA) intake was not connected to the HVAC system. When two windows were opened to provide cross ventilation in a guest room, the C_{HCHO} monitor readings dropped to < 10 ppb at night.

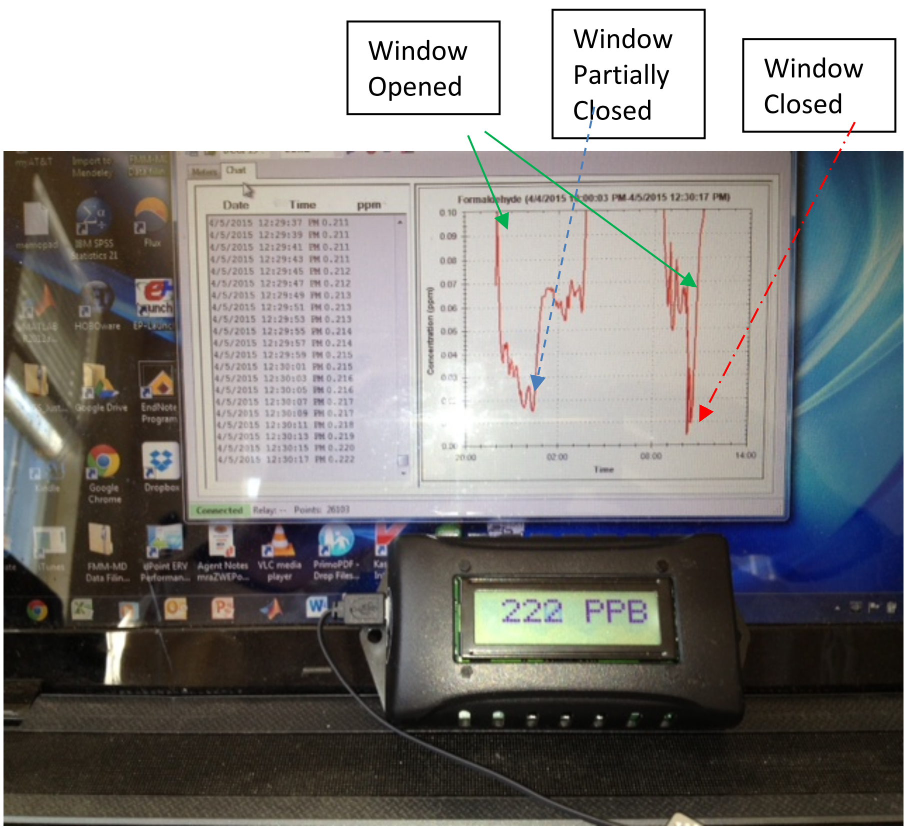


Figure 9.6: Impact of Opening Window on C_{HCHO} in a Residence.

A dashboard output of data from the HCHO monitor is shown in Figure 9.7.

Figure 9.7: Dashboard Output of HCHO Monitor

9.4.2 Location B: Impact of a Printer and HVAC Cycling

Location B is a residence that is in the 5th percentile of C_{HCHO} in homes based on the database developed in Chapter 3. Monitor #11 was located in a home office for 24-hours as shown in Figure 9.8. The large spikes around 10 AM and 8:30 PM are from using an inkjet printer. Likely some cross-sensitivity to alcohols in the ink are involved. The sinusoidal oscillations throughout the day are thought to be from the cycling of the HVAC cooling coil, which would wash some HCHO out of the air on the wet coil. The gradual increase from 2 PM to 6 PM is thought to be due to a thermal effect as the monitor was located in a room with a large west facing window. These results led to adding a T and %RH sensor to the 7th generation HCHO monitor design so that cycling of C_{HCHO} can be isolated from the impact of T and %RH variation on the monitor output in future work.

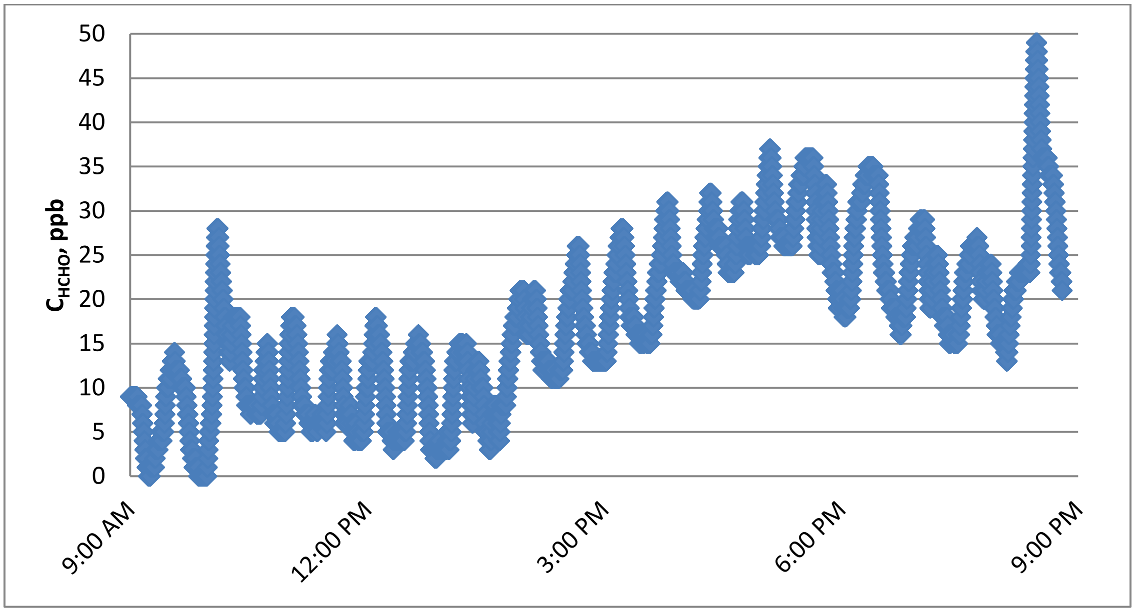


Figure 9.8: 24-hour Output of HCHO Monitor in Low C_{HCHO} Residence

The 24-hour average of the C_{HCHO} data shown in Figure 9.8 is 18 ppb, which is within the measurement error of the NIOSH concentration (16 ppb) required in manufactured housing. Based on the calibration data shown in Figure 9.2, the concentrations shown in Figure 9.8 are +/- 6 ppb due to off-set variation. Additional variation due to cross-sensitives to any other aldehydes, alcohols, CO, etc., in this all electric home without any combustion sources or an attached garage are unknown. Future field trials where simultaneous 24-h air samples are collected and analyzed using DNPH (2,4-Dinitrophenylhydrazine) can provide additional information on the accuracy of this monitor in the built environment.

9.5 Thermal Control in Transit

The sensor used in the MCC HCHO monitor has a 40 ^{o}C thermal storage limit. Temperatures encountered in transit may exceed this temperature (for instance in the back of a car, or delivery service vehicle in Texas in the summer). To address this concern, a packaging system using phase change materials (PCM) that limits thermal exposure during multi-day transport during the summer was explored as shown in Figure 9.9.

Figure 9.9: Phase Change Material Thermally Controlled Packing Solution

To test this packing solution, the packaging was placed in the back seat of a vehicle in Texas and parked in the sun. Temperatures inside and outside the packaging were monitored for 108 hours (more than 4 days). As shown in Figure 9.10, while the temperature outside the box reached 50 oC, the inside of the shipping container never exceeded 30 ^{o}C providing a 10 ^{o}C “cushion” for the requirement that the device never exceed 40 ^{o}C.

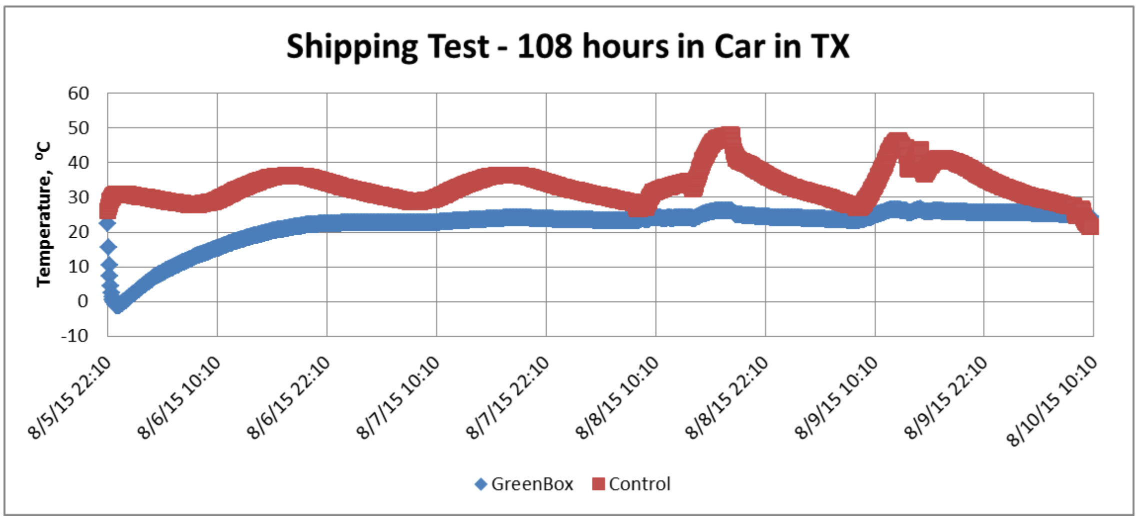


Figure 9.10: Shipping Test in a Vehicle in Texas in Summer

A similar PCM packaging solution (using a lower temperature PCM) could be explored by others for use with the Shinyei or other HCHO sensors with lower temperature limits.

9.5 Future Work

9.5.1 Temperature, %RH dependence and Cross-sensitivity

Temperature and %RH dependence on the sensor is relatively straight-forward to correct with calibrated sensors. The 7th generation HCHO monitor design incorporates a temperature and humidity sensor for this purpose.

Cross-sensitivity to other contaminants is the largest concern identified with use of the HCHO monitor. Two approaches are contemplated to resolve these issues:

1. Use of independent sensors for CO and EtOH that can be provide concentrations of these key contaminants that can be subtracted from the C_{HCHO} results measured by the HCHO monitor.
2. Use of a selective semi-permeable membrane to separate CO, EtOH and other aldehydes from formaldehyde. Table 9.5 provides information on the kinetic diameter, molecular weight and boiling point of the key chemicals of interest. Differences in kinetic diameter of formaldehyde and potentially cross-sensitive compounds (Carbon monoxide and acetaldehyde and lower molecular weight alcohols) is intriguing and suggest that separation by use of a semi-permeable membrane may be feasible.

Table 9.5: Kinetic diameter of low MW gases

Compound	Kinetic Diameter (Å)	Molecular Weight (g/mole)	Boiling Point (°C)
Formaldehyde	2.43	30.03	-19.5
Water	2.68	18.02	373
Carbon Dioxide	3.3	44.01	-78.5
Oxygen	3.46	32.00	-182.96
Nitrogen	3.64	28.01	-195.79
Carbon Monoxide	3.76	28.01	-191.5
Acetaldehyde	3.8	44.05	20.1
Methane	3.8	16.04	-161.50
Methanol	3.8-4.2	32.04	64.7
Ethanol	4.5	46.08	78.37

The concept of a selective semi-permeable membrane was briefly considered to accomplish a separation of HCHO and Ethanol of a factor of 10. Using a selective membrane would require pressurizing the gas to overcome the resistance of the membrane and would significantly increase the cost of the monitor. Pursuing this approach is beyond the scope of this study and is left to future work.

9.6 Summary

Work to date on the formaldehyde monitor has demonstrated that it is very sensitive to formaldehyde at concentrations of 16 ppb and lower in a controlled laboratory environment. Preliminary testing has also shown that the HCHO sensor is cross-sensitive to ethanol, isopropanol, and, to a lesser extent acetaldehyde. By using the database developed in Ch. 3, the key cross-sensitivity of concern is ethanol. Even without removal of ethanol, >95% of the samples in the database are expected to read within +/-25% of the true formaldehyde concentration.

Phase 1 of this dissertation provides the database and DALY analysis which informed the impact of assumed cross-senstvities of the HCHO monitor in Chapter 9 and the value of the potential health impacts of elevated exposure to formaladehyde. Phase 2 provides the energy analysis of the source reduction, ventilation and gas-phase filtration scenarios to optimize energy and C_{HCHO}, and Phase 3 provides a key component, a formaldehyde monitor that may be used to optimize the sourcd reduction, ventilation and gas-phase filtration scenarios studied in Phase 2.

Chapter 10 summarizes the work done in this dissertation, relevant publications and provides a vision for potential future work to fully deploy a real-time formaldehyde monitor to optimize IAQ (using HCHO as a metric) and energy use in homes.

Chapter 10 Summary, Conclusions and Future Work

10.1 Major Research Outcomes and Findings

This dissertation involved several major components. First, a new database of 296 sampling events in 249 homes was developed to explore whether formaldehye (HCHO) is a good metric for the impact of all volatile organic compounds (VOCs), including aldehydes, collected in 24-hour air samples (Chapter 3). Second, field work and analysis completed at Oak Ridge National Laboratories involved collection of data and subsequent correlations between the concentation of formaldehyde (C_{HCHO}) and environmental parameters for two energy efficient test homes (Chapter 4 and 5). Third, these correlations were used in conjunction with the EnergyPlus™ and the FREE models to determine the additional energy, above that used when the two energy-effiient houses were ventilated to ASHRAE 62.2-2016 minimum ventilation requirements, required to achieve desired reference exposure limits for formaldehyde for both house designs in the eight U.S. climate zones (Chapter 6-8). The energy savings that could be achieved from use of a real-time formaldehyde monitor were part of this analysis. Fourth, a new real-time formaldehyde monitor was explored with initial testing of efficacy in measuring formaldehyde under controlled laboratory conditions and the impact of cross-sensitivity of the formaldehyde sensor to alcohols and aldehydes.

This collective effort provided:

1. A database of VOCs, including aldehydes from 296 sampling events in 249 homes. This original contribution to the literature provides additional data showing concentrations of chemicals in single-family detached homes and compares well with a database related to HCHO concentrations in 109 new California homes (Offermann, 2009). This provides strong evidence that HCHO is a good metric for the impact of VOCs and other aldehydes on indoor air quality (IAQ). (Chapter 3)
2. Strong evidence that formaldehyde is the predominant VOC contaminant of concern in the database of residential homes using a disability adjusted life years (DALYs) approach. (Chapter 3)
3. Correlations for indoor HCHO concentrations based on indoor tempertuare (T_{in}), and total air exchange rate (λ_{tot}), using field work and modeling for two test homes as reported by Hun et al. (2013a) (Appendix A). (Chapters 4 and 5)
4. The energy required for ventilation or gas phase filtration to achieve desired reference exposure limits (REL) for HCHO in both house designs in eight climate regions in the United States.
5. The value, in terms of DALYs saved and energy cost, of achieving specific RELS for HCHO in both house designs in eight climate regions in the United States. (Chapters 7 and 8)
6. The value in terms of energy savings of using a real-time HCHO monitor to control variable speed ventilation in the two test homes in eight climte regions

in the United States. Had ERV fan energy been included in the detailed analysis the value of the real-time HCHO monitor for the ERV scenarios would be higher as ventilation energy is reduced when real-time ventilation control is used (Chapter 8).

7. Demonstration of a real-time HCHO monitor that can perform down to 16 ppb or less and the impact of cross-sensitivities to other chemical contaminants in a home. (Chapter 9)

10.2 Publications

The work done, in part, to support this dissertation has been published and presented elsewhere as described below:

Publications:

Carter, E.M., Jackson, M.C., Katz, L.E., Speitel, G.E, 2013. "A Coupled Sensor-Spectrophotometric Device for Continuous Measurement of Formaldehyde in Indoor Environments." Journal of Exposure Science and Environmental Epidemiology, 1-6. (A pre-publication version is shown in Appendix G)

Hun, D., Shrestha, S., and Jackson, M., 2013. Optimization of Ventilation Energy Demands and Indoor Air Quality in ZEBRAlliance Homes, ORNL/TM-2013/275. Oak Ridge. (Appendix A)

Hun, D.E., Jackson, M.C., and Shrestha, S.S., 2013b. Ventilation Energy Demands and Indoor Air Quality in High-Performance Homes, Interface 31 (9): 39-46.

Hun, D.E., Jackson, M.C., 2014. Intermittent Ventilation Energy Demands and Indoor Air Quality in Mixed-Humid Climates, ORNL/TM-2014/136. Oak Ridge. (Appendix H)

Conference Papers with Oral Presentations:
(presentations by Jackson)

Stephens, B., & Jackson, M. C. (2009). Contribution of Wall Cavity Insulation to Formaldehyde Levels in a Space. In *Proceedings of Healthy Buildings 2009* (Paper #514). Syracuse, NY: ISIAQ.

Jackson, M.C., Penn, R. L., Aldred, J. R., Zeliger, H. I., Cude, G. E., Neace, L. M., Kuhs, J.F., Corsi, R. L. (2011). Comparison Of Metrics For Characterizing The Quality Of Indoor Air. In *Proceedings of IndoorAir2011* (Paper #a115). Austin, TX: ISIAQ.

Conference Abstracts with Poster Presentation:
(presentation by Jackson)

Jackson, Mark C, Penn, R. L., Cude, G. E., Neace, L. M., & Kuhs, J. F. (2011). Formaldehyde : How Low Can We Go? In Proceedings of *IndoorAir 2011* (Paper #a136). Austin, TX; ISIAQ

10.3 Limitations of Research

While the research conducted for this dissertation was extensive, it has several limitations, particularly in regard to the relevancy of the emission rates of HCHO measured in two very specialized, energy efficient buildings to a broader housing stock. Specific limitations include:

1. Correlations for formaldehyde concentration were determined using data from two highly energy efficient test homes at ORNL. Both houses had unique energy saving features. House WC-2, generally considered to be the design most likely to be replicated by builders, had a total ventilation rate as low as 0.017 ACH, which is one of the lowest ventilation rates found

in the literature for an energy efficient home. House WC-3, generally considered to be unlikely to be replicated (phase change material in the walls) had C_{HCHO} that were in the 99th percentile of the database and thus not representative of a broader housing stock.

2. The correlations obtained for both test homes were based on limited amounts of data that were not spread throughout an entire year and did not have measurements during extreme cold weather. This may have led to C_{HCHO} predictions being higher than would actually occur during the winter months.
3. The VOC database included data from air samples that were not collected by certified individuals, and thus may have had sampling errors in both how the samples were taken and sampling times. This was mitigated to some extent by the criteria used in accepting the samples.
4. The VOC database did not have any data on ventilation rates, but only measured individual VOC concentrations in an occupied space. Temperature, humidity and ventilation measurements were also not measured.
5. Laboratory testing of the formaldehyde monitor was resource constrained so that there were few replicate samples.
6. The formaldehyde monitor was tested as a prototype that is still under development. Hardware design errors in the 7th Generation design prevented full measurement of the zero off-set. Software errors prevented

utilizing the temperature and humidity results. While these errors are currently being corrected, resource limitations have prevented full resolution of the issues, manufacturing of additional monitors and retesting multiple units.

7. Work done on the HCHO monitors revealed sensor response to components of the monitors, including plastics, printed circuit boards, and some wire insulation. When working at single digit ppb concentrations of HCHO, these relatively minor interferences contributed to the overall uncertainty of the measurements. Solutions for these material issues are being addressed in future work.

10.4 Research Path Forward

This work has provided the basic information needed to justify the development of an advanced IAQ monitoring and ventilation control system based on formaldehyde. However, additional work is needed to:

1. Evaluate a larger number of house designs in different geographic regions and include a full analysis of the impact of ERV fan energy and filtration of outdoor air with higher efficiency particulate filters and

carbon in commercially available combined ERV/ventilation filtration equipment,

2. Fully develop a formaldehyde monitor/controller and integrate it with energy efficient ventilation equipment, and
3. Demonstrate the performance of such a system over a full year in (a) test home(s).

Evaluation of additional homes to characterize the whole-home HCHO emission rate based on the ventilation rate and environmental parameters is described in Section 10.4.1 Additional testing needed for the HCHO monitor are described in Section 10.4.2. Finally, a field trial, to implement an HCHO monitor to control an enhanced ventilation system that is currently partially manually controlled is described in Section 10.4.3.

10.4.1 Evaluation of HCHO emissions in additional homes

To provide sufficient data to potentially generalize the correlation between indoor temperature and air exchange rate (an increase in λ_{tot} of ~0.1 h^{-1} has approximately the same impact on C_{HCHO} as a decrease in T_{in} of ~ 1 ^{o}C found in the two test homes studied Chapter 5), additional homes of different designs and in different locations need to be evaluated. Ideally, such a study would involve on the order of 100 occupied homes spread across all 8 Building America Geographic regions. Real-time measurements of C_{HCHO}, T_{in}, $\%RH_{in}$, and λ_{tot} in addition to meteorological data [T_{out}, $\%RH_{out}$, wind speed (WS)] are needed. Sherman (2016) has suggested that measuring the flow rate of mechanical ventilation (i.e. measured with a flow hood) with subsequent estimation of λ_{inf} is a lower cost, possibly more accurate, way of measuring real-time λ_{tot} than tracer gas approaches.

Time resolved measurements of C_{HCHO} could not only provide a way of optimizing energy used for ventilation, as shown in Chapters 6-8, but also help identify the impact of temporal sources of HCHO in an occupied home, including cooking, combustion activities (candles, gas appliances, etc.), cleaning, and use of certain personal care products.

10.4.2 Additional Testing of HCHO Monitor:

The following should be priorities for future improvement and testing of the HCHO monitor described in this study.

- Evaluate off-set stability and cross-sensitivity with a modified monitor, including the potential to remove EtOH, acetaldehyde and, inorganic gases to improve selectivity of the sensor.

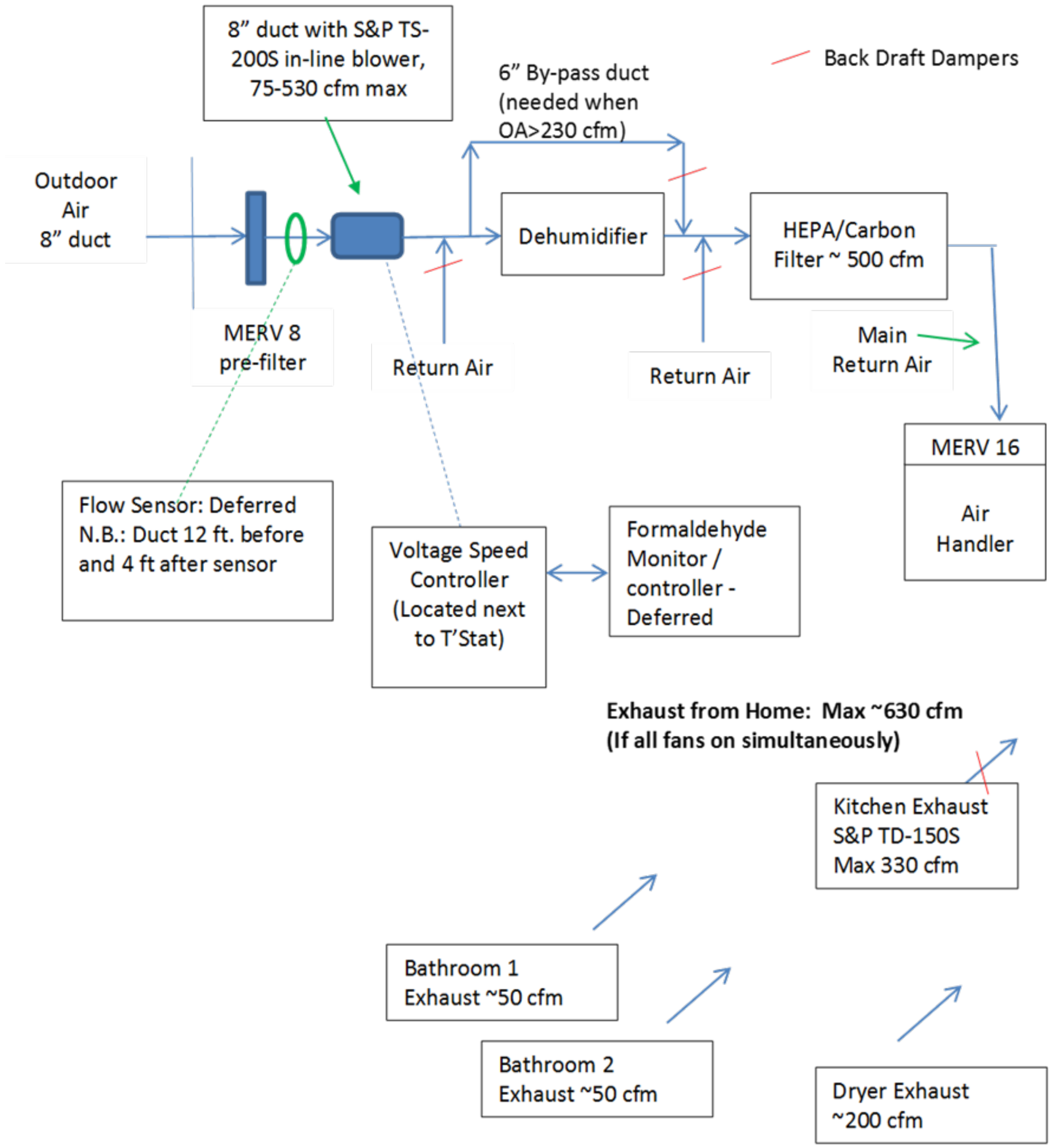
- Determine impact of temperature transients (i.e. in transportation or storage) on off-set and calibration of sensor (i.e. store sensor in the freezer for 24 hours and place in an oven at 40 ^{o}C for 24 hours and measure impact on calibration at 0 and 81 ppb).
- Determine impact of relative humidity on off-set and calibration of sensor (15% - 60% RH)
- Complete additional cross-sensitivity evaluations of HCHO sensor for carbon monoxide, inorganic gases (H_2, SO_2, NO_X, Cl_2) and phenol.
- Conduct a field trial of HCHO monitor and assess its potential to control ventilation – as described in the following section.

10.4.3 Field Trial of HCHO Monitor/Ventilation Controller

An advanced ventilation system as shown in Figure 10.1 that can provide adjustable mechanical ventilation of 0 to more than 1.0 h^{-1} was installed in an occupied home in 2015. The outdoor air is filtered and dehumidified prior to introduction to the air handler for circulation throughout the home. To provide point source ventilation of a key source of contaminants in this home, current sensing relays are used to automatically turn on kitchen exhaust when the stove, oven, microwave, toaster, or coffee maker are turned on. A 10-minute delay timer is used to continue ventilation after the kitchen appliances are turned off.

Currently, mechanical ventilation is manually controlled by the homeowner using an adjustable voltage controller to adjust the fan speed of the outdoor air blower that is located next to a wall mounted thermostat. Future plans include addition of the formaldehyde monitor/controller described in Chapter 9 to control mechanical ventilation based on C_{HCHO}, indoor temperature (T_{in}) and indoor relative humidity ($\%RH_{in}$).

Figure 10.1: Advanced Ventilation System Installed in Occupied Home



Appendices

Appendix A: ORNL/TM-2013/275

See supplemental file for article.

Hun, D.E., Jackson, M.C., Shrestha, S.S (2013) Optimization of Ventilation Energy Demands and Indoor Air Quality in ZEBRAlliance Homes, ORNL/TM-2013/275.

My contribution was collecting the field data and computer modeling.

Appendix B: Summary of Sampling Events in Database

Table B.1: Details of Sampling Events in Database

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
1	S	WSC	7/08	23:00	1	1	1			
2	S	WSC	8/08	24:18	avg 2&3	2	2		1	2
3	S	WSC	12/08	24:00	4	3		9	2	1
4	ON*	ON*	12/08	24:00	5	4	3			
5	NE	NE	1/09	25:15	6	5		6	2	1
6	S	WSC	2/09	24:23	7	6	4			
7	S	SA	3/09	24:26	8	7	5			
8	MW	ENC	4/09	24:00	9	8		14	2	1
9	S	WSC	3/09	24:00	10	9	6			
10	S	WSC	5/09	24:00	11	10	7			
11	MW	ENC	5/09	24:00	12	8		14	2	1
12	MW	ENC	4/09	24:00	13	11	8			
13	S	WSC	5/09	24:00	avg 14&15	12	9		1	2
14	S	WSC	6/09	24:00	16	13	10			
15	MW	WNC	6/09	24:00	17	14	11		1	1
16	MW	ENC	7/09	24:00	18	15		29	2	1
17	W	P	9/09	24:00	19	16	12			
18	S	WSC	10/09	24:00	20	17		21	6	1
19	MW	ENC	10/09	24:00	21	18	13			
20	MW	ENC	10/09	24:00	22	19	14			
21	S	WSC	10/09	24:00	23	20		25	2	1
22	MW	ENC	10/09	24:00	24	21	15			
23	S	WSC	10/09	24:00	25	3		9	2	1
24	PRR*	AB*	11/09	24:55	26	22	16			
25	S	SA	12/09	24:31	27	23	17			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
26	S	WSC	1/10	24:00	28	17		21	6	1
27	MW	ENC	12/09	24:00	29	15		29	2	1
28	S	WSC	12/09	24:00	avg 30 & 31	24	18		1	2
29	S	WSC	12/09	24:00	avg 32&33	25	19		1	2
30	S	WSC	1/10	24:00	34	26	20			
31	MW	WNC	1/10	24:00	35	27	21			
32	MW	ENC	1/10	24:00	36	28	22			
33	S	WSC	1/10	24:00	37	29	23			
34	S	WSC	2/10	24:00	38	30	24			
35	S	WSC	2/10	24:00	39	31	25			
36	S	SA	2/10	24:00	40	32	26			
37	W	P	2/10	24:00	41	33		20	3	1
38	NE	NE	2/10	24:00	42	5		6	2	1
39	S	WSC	3/10	24:00	43	34	27		1	1
40	S	WSC	3/10	24:00	44	35	28			
41	S	WSC	3/10	24:00	45	17		21	6	1
42	NE	MA	3/10	24:00	46	36	29			
43	S	WSC	3/10	24:00	47	17		21	6	1
44	NE	MA	3/10	24:00	48&49	37		24	2	2
45	W	P	3/10	24:00	50	38	30			
46	S	WSC	3/10	24:00	51	17		21	6	1
47	S	WSC	4/10	24:00	52	17		21	6	1
48	S	WSC	4/10	24:00	53	20		25	2	1
49	S	WSC	4/10	24:00	54	39		17	4	1
50	S	WSC	4/10	25:00	55	40	31			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
51	S	WSC	4/10	23:30	56	41	32			
52	W	P	5/10	24:00	57	33		20	3	1
53	S	WSC	5/10	24:00	58	42	33			
54	W	P	5/10	24:00	59	33		20	3	1
55	W	M	6/10	24:00	60	43		26	2	1
56	S	WSC	6/10	23:46	61 & 62	39		17	4	2
57	S	WSC	7/10	24:00	63	44	34		1	1
58	S	WSC	8/10	24:37	64	45	35			
59	S	WSC	8/10	25:37	65	46	36		1	1
60	S	SA	8/10	24:00	66	47	37			
61	S	WSC	8/10	24:00	67	48	38			
62	S	WSC	9/10	22:41	68&69	39		17	4	2
63	NE	MA	8/10	24:19	70	37		24	2	1
64	S	WSC	9/10	24:17	71	49	39			
65	W	P	9/10	24:15	72	50	40			
66	S	SA	9/10	24:00	73	51	41			
67	W	P	10/10	24:00	74	52	42			
68	S	WSC	10/10	24:13	75	53	43			
69	W	M	10/10	23:45	76	43		26	2	1
70	S	SA	11/10	24:00	77	54		10	2	1
71	S	WSC	11/10	22:30	78	55	44			
72	S	WSC	11/10	24:05	79	56	45		1	1
73	S	ESC	11/10	24:37	80	57	46			
74	S	WSC	12/10	23:30	81&82	54		10	2	2
75	S	WSC	12/10	24:08	83	58	47			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
76	S	WSC	12/10	23:26	84	59	48			
77	S	WSC	12/10	24:00	85&86	60	49		1	2
78	MW	WNC	1/11	24:04	87	61	50			
79	S	WSC	1/11	24:15	88	62	51			
80	MW	ENC	1/11	23:30	89	63	52			
81	MW	ENC	1/11	23:30	90	64	53			
82	MW	WNC	1/11	24:28	91	65	54			
83	S	WSC	1/11	24:00	92	66	55			
84	MW	ENC	1/11	23:55	93	67	56			
85	W	M	2/11	24:00	94	68	57			
86	NE	MA	2/11	24:35	95	69	58			
87	S	WSC	2/11	24:13	96	70	59			
88	S	SA	2/11	24:00	97	71	60			
89	S	WSC	2/11	24:00	98	72	61			
90	S	WSC	3/11	24:00	99	73		5	2	1
91	S	WSC	3/11	24:20	100	74	62			
92	S	WSC	3/11	25:05	101	75	63			
93	S	WSC	3/11	24:05	102	76	64			
94	S	WSC	3/11	24:33	103	77	65			
95	S	WSC	3/11	22:00	104	78	66			
96	MW	ENC	3/11	24:00	105	79	67			
97	S	WSC	3/11	23:45	106	80	68			
98	S	WSC	3/11	24:36	107	81	69			
99	S	WSC	3/11	25:38	108	82	70			
100	W	M	4/11	24:10	109	83	71			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	*House #*	*SSEH#*	*MSEH#*	*# SEs in House*	*# Samples in SE*
101	MW	ENC	3/11	24:00	110	84	72			
102	S	WSC	3/11	24:20	111	85	73			
103	S	SA	4/11	23:55	112	86	74			
104	S	WSC	4/11	24:00	113	87	75			
105	S	SA	4/11	24:07	114	88	76			
106	S	SA	5/11	23:00	115	89	77			
107	S	WSC	5/11	24:02	116	90	78			
108	S	WSC	5/11	24:40	117	91	79			
109	S	ESC	6/11	24:00	118	92	80			
110	S	WSC	6/11	23:00	119	93	81			
111	S	WSC	6/11	23:33	120	94	82			
112	S	WSC	6/11	23:01	121	95	83			
113	S	SA	6/11	23:46	122&123	96		22	2	2
114	S	WSC	6/11	25:00	124	97	84			
115	S	WSC	6/11	24:00	125	98		3	2	1
116	S	ESC	6/11	24:00	126	99	85			
117	S	SA	7/11	24:00	127	100	86			
118	NE	NE	7/11	23:58	128,129&130	101	87		1	3
119	S	WSC	7/11	23:30	131	102	88			
120	S	WSC	7/11	24:00	132	103	89			
121	W	M	9/11	24:15	133	104	90			
122	S	WSC	9/11	25:30	134	105	91			
123	S	ESC	8/11	24:00	135	106	92			
124	S	ESC	8/11	24:54	136	107		33	2	1
125	S	ESC	8/11	25:00	137	108		34	2	1

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
126	S	SA	9/11	26:00	138	109	93			
127	S	WSC	9/11	23:03	139	110	94			
128	S	WSC	9/11	23:45	140&141	73		5	2	2
129	S	WSC	9/11	22:58	142	111	95			
130	S	SA	9/11	24:00	143	112	96			
131	S	WSC	10/11	24:15	144	113	97			
132	S	ESC	10/11	25:35	145	114	98			
133	S	SA	12/11	24:00	146	115	99			
134	S	SA	12/11	24:04	147	116	100			
135	S	WSC	11/11	23:30	148	117		19	2	1
136	S	SA	11/11	25:10	149	118	101			
137	S	SA	10/11	23:44	150	119	102			
138	S	SA	10/11	24:40	151	120	103			
139	S	ESC	11/11	24:00	152	107		33	2	1
140	S	ESC	11/11	24:00	153	121	104		1	1
141	S	ESC	11/11	24:00	154	108		34	2	1
142	S	ESC	11/11	24:00	155	122	105		1	1
143	S	SA	12/11	23:25	156	123	106			
144	S	WSC	12/11	23:50	157	124	107			
145	S	ESC	12/11	24:00	158	125	108			
146	S	ESC	12/11	24:00	159	126	109			
147	S	WSC	12/11	23:41	160	127	110			
148	S	SA	1/12	24:10	161-164	96		22	2	4
149	S	WSC	1/12	24:00	165	128	111			
150	MW	ENC	2/12	25:00	166	129	112			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
151	S	WSC	2/12	24:05	167	130		2	2	1
152	S	WSC	2/12	24:00	168	131	113			
153	W	P	3/12	24:15	169	132	114			
154	S	SA	3/12	24:07	170	133	115			
155	S	WSC	3/12	23:45	171	134	116			
156	S	SA	3/12	24:30	172	135	117			
157	S	WSC	3/12	24:35	173	130		2	2	1
158	S	SA	3/12	22:00	174	136	118			
159	S	SA	3/12	24:00	175	137	119		1	1
160	W	M	3/12	24:20	176	138	120			
161	S	WSC	4/12	25:30	177	39		17	4	1
162	S	WSC	4/12	23:45	178	139	121			
163	S	SA	4/12	24:34	179	140	122			
164	MW	ENC	5/12	23:45	180	141	123			
165	S	WSC	5/12	23:25	181	142	124			
166	MW	ENC	5/12	24:00	182	143	125			
167	NE	NE	5/12	22:30	183&184	144		16	2	2
168	S	WSC	6/12	24:04	185	145	126			
169	S	WSC	6/12	24:10	186	146	127			
170	S	WSC	6/12	24:30	187	147	128			
171	S	WSC	6/12	24:00	188	148	129			
172	NE	MA	6/12	24:00	189&190	149	130		1	2
173	NE	MA	6/12	24:17	191&192	150		15	2	2
174	S	WSC	7/12	24:46	193	151	131			
175	S	WSC	7/12	23:00	194	152		31	3	1

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
176	MW	WNC	7/12	24:28	195	153	132			
177	W	M	7/12	24:00	196	154		7	3	1
178	S	WSC	8/12	23:56	197	152		31	3	1
179	S	SA	8/12	24:00	198	155	133			
180	MW	WNC	9/12	24:15	199	156	134			
181	NE	NE	9/12	23:46	200&201	157	135		1	2
182	S	WSC	9/12	23:55	202	158	136			
183	MW	ENC	9/12	24:00	203	159	137			
184	S	WSC	9/12	24:00	204	98		3	2	1
185	S	WSC	9/12	23:56	205	152		31	3	1
186	S	SA	9/12	25:33	206,207&208	160		4	2	3
187	MW	ENC	10/12	24:45	209	161	138			
188	S	SA	10/12	24:00	210	162	139			
189	S	WSC	10/12	25:06	211	163	140			
190	S	WSC	10/12	24:05	212	164	141			
191	S	WSC	11/12	25:45	213	165	142			
192	S	WSC	11/12	24:00	214	166	143			
193	S	SA	11/12	24:12	215	167	144			
194	S	WSC	11/12	24:00	216	168	145			
195	S	SA	11/12	23:41	217	169		1	3	1
196	S	SA	11/12	24:30	218	160		4	2	1
197	MW	ENC	11/12	25:15	219	170	146			
198	S	ESC	12/12	24:00	220	171	147		1	1
199	S	ESC	12/12	24:00	221	172	148		1	1
200	S	WSC	12/12	24:20	222	173	149			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
201	NE	MA	12/12	24:00	223	174		18	2	1
202	MW	WNC	12/12	24:12	224	175	150			
203	S	WSC	1/13	24:25	225	176	151			
204	S	SA	1/13	24:00	226&227	169		1	3	2
205	MW	ENC	1/13	24:18	228	177		32	2	1
206	S	WSC	1/13	24:30	229	178	152			
207	MW	ENC	1/13	24:35	230	179	153			
208	S	WSC	2/13	24:43	231	180	154			
209	S	SA	2/13	23:54	232&233	181	155		1	2
210	S	SA	2/13	23:29	234&235	169		1	3	2
211	S	WSC	2/13	24:15	236	182	156			
212	S	SA	3/13	24:00	237	183	157			
213	W	M	3/13	23:50	238	154		7	3	1
214	S	WSC	3/13	24:00	239	184	158			
215	S	SA	3/13	24:00	240	185	159			
216	S	WSC	4/13	24:00	241	186	160			
217	S	WSC	4/13	24:00	242	187		23	3	1
218	MW	ENC	4/13	25:00	243	177		32	2	1
219	S	SA	4/13	24:16	244	188		8	3	1
220	NE	MA	4/13	23:43	245&246	189		13	2	2
221	MW	ENC	4/13	24:10	247	190	161			
222	S	WSC	4/13	24:00	248	191	162			
223	S	SA	4/13	23:00	249	192	163		1	1
224	MW	ENC	5/13	23:51	250	193	164			
225	S	WSC	5/13	24:30	251	194	165			

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
226	S	WSC	5/13	23:53	252	195	166			
227	MW	ENC	5/13	25:25	253	196	167			
228	S	WSC	5/13	23:37	254	197		27	2	1
229	MW	ENC	6/13	24:07	255	198	168			
230	S	SA	5/13	24:00	256	199	169			
231	NE	NE	6/13	24:00	257	200	170			
232	S	SA	6/13	24:00	258	201		30	3	1
233	S	SA	7/13	24:00	259	188		8	3	1
234	S	SA	7/13	24:04	260	201		30	3	1
235	S	SA	7/13	24:00	261	202	171			
236	S	WSC	8/13	23:15	262	203	172			
237	MW	ENC	8/13	24:10	263	204	173			
238	MW	ENC	9/13	24:04	264	205	174			
239	S	WSC	8/13	24:00	265	206	175			
240	MW	ENC	9/13	24:56	266	207	176			
241	S	SA	8/13	23:44	267&268	208	177		1	2
242	W	M	9/13	24:00	269	209	178			
243	S	WSC	9/13	22:52	270&271	210	179		1	2
244	NE	NE	8/13	24:00	272,3,4,5,6	211		11	2	5
245	S	WSC	10/13	22:55	277	212	180			
246	NE	MA	10/13	24:00	278	144		16	2	1
247	NE	MA	10/13	24:00	279	174		18	2	1
248	MW	ENC	10/13	24:00	280	213	181			
249	W	P	10/13	25:15	281	214	182			
250	S	SA	10/13	24:12	282&283	215	183		1	2

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
251	MW	ENC	11/13	25:07	284	216	184			
252	S	WSC	11/13	24:09	285	217		12	2	1
253	S	WSC	11/13	25:30	286	218	185			
254	S	WSC	11/13	24:00	287	219	186			
255	NE	MA	11/13	24:19	288,289&290	150		15	2	3
256	S	WSC	11/13	24:00	291	220	187		1	1
257	S	WSC	12/13	24:15	292	197		27	2	1
258	S	SA	12/13	25:03	293&294	188		8	3	2
259	S	SA	12/13	24:18	295&296	201		30	3	2
260	S	SA	12/13	24:22	298&299	221	188		1	3
261	W	P	12/13	25:10	300	222	189			
262	S	SA	12/13	24:10	301	223	190			
263	S	WSC	1/14	24:33	302	224	191			
264	MW	ENC	1/14	23:52	303	225	192			
265	MW	ENC	1/14	24:00	304	226	193			
266	MW	ENC	1/14	25:00	305	227	194			
267	S	WSC	1/14	24:00	306	228	195			
268	MW	ENC	1/14	24:00	307	229	196			
269	NE	NE	2/14	25:30	308	211		11	2	1
270	S	WSC	3/14	24:12	309&310	187		23	3	2
271	S	WSC	3/14	24:05	311	230	197			
272	MW	ENC	3/14	24:00	312	231	198			
273	S	SA	3/14	24:26	313	232	199		1	1
274	S	SA	3/14	24:04	314	233	200			
275	S	SA	5/14	23:25	315&316	234	201		1	2

Table B.1: Details of Sampling Events in Database (cont.)

SE#	Geographical Region	Geographical Division	Sampling Date (MM/YY)	Sampling Time (HH:MM)	Sample #	House #	SSEH#	MSEH#	# SEs in House	# Samples in SE
276	S	WSC	5/14	23:40	317	235	202		1	1
277	S	WSC	5/14	23:25	318	236	203		1	1
278	W	M	5/14	25:00	319	154		7	3	1
279	MW	ENC	6/14	24:20	320	237		28	2	1
280	S	WSC	7/14	24:20	321	187		23	3	1
281	MW	ENC	7/14	24:00	322	237		28	2	1
282	S	WSC	7/14	24:00	323	238	204			
283	S	SA	7/14	24:30	324	239	205			
284	S	WSC	7/14	24:00	325	117		19	2	1
285	S	WSC	7/14	23:00	326	240	206		1	1
286	S	WSC	7/14	24:00	327	217		12	2	1
287	NE	MA	8/14	24:00	328	189		13	2	1
288	W	M	8/14	24:05	329	241	207		1	1
289	NE	NE	8/14	24:25	330	242	208			
290	W	M	8/14	24:30	331	243	209			
291	S	SA	8/14	23:58	332	244	210			
292	NE	NE	9/14	25:15	333,334,&335	245	211		1	3
293	NE	NE	7/14	25:20	336	246	212			
294	S	WSC	9/14	24:02	337	247	213			
295	S	SA	9/14	25:00	338&339	248	214		1	2
296	S	ESC	10/14	23:00	340	249	215		1	1

Appendix C: Air Exchange Rate (λ_{tot}) Protocol

Air Exchange Rate (λ_{tot}) Protocol

Reference:

ASTM, 2006, Standard E 741-00 (Reapproved 2006): Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution

Equipment:

- INNOVA AirTech Instruments 1303 Multipoint Sampler and Doser
- INNOVA AirTech Instruments 1412 Photoacoustic Field Gas Monitor
- ¼" Teflon sampling tubing of sufficient length to reach adjacent spaces
    - Tubing is labeled with labels on end of tube that attaches to INNOVA:
        - Channel 1: for AER test, runs from Innova in closet of MBRM to 1st floor living area – tape to thermostat.
            - Note: For IZF test, Channel 1 is the 1st floor living area in this set-up and as it is in that zone, no tubing is needed.
        - IAQ S2, IZF 2nd Floor – runs from INNOVA to the 2nd floor – insert in Sampler Ch 2
        - IZF Garage S3 – runs from INNOVA to the garage – insert in Sampler Ch 3
        - IZF S4 Attic – runs from INNOVA to attic above Master Bedroom Walk-in Closet – insert in Sampler Ch 4
        - IZF S5 Crawlspace – runs from INNOVA to crawlspace through hole in floor between wall of living room closet and utility room – insert in Sampler Ch 5
- Tracer Gas: Target Concentration is 4 ppm
    - R134a – use for AER measurements
    - Sulfur Hexafluoride (SF6) cylinder and regulator.
        - Use ONLY for IZF measurements with a 2nd gas is required.
- Use R134a cylinder.

- 1 Liter Teflon bag, if SF_6 is used, to judiciously distribute Tracer Gases
- Blue tape for securing tubing (does not pull paint off when remove)

Locating the INNOVA units and ¼” Teflon sampling tubing:

- For AER test, locate INNOVA units in closet of Master Bedroom
    - String ¼” Teflon™ sampling tubes from port 1 & 2 on the INNOVA 1303 in the closet to the 1st floor living room and the 2nd floor living area respectively. Well mixed conditions for the house are demonstrated when tracer gas concentrations measured by the INNOVA from the 1st and 2nd floor are the same.

INNOVA Set-up:

- See Figure C.1.
- Place INNOVA 1412 Photoacoustic Field Gas Monitor on the floor
- Place INNOVA 1303 Multipoint Sampler and Doser on top
- Place DELL laptop with INNOVA software and green Dongle on top

Figure C.1: Equipment Set-up – Front View

- DO NOT connect power strip to power outlet on wall yet.
- There are seven (7) things to connect on the back of the INNOVA/computer stack (see Figure C.2):
    1. Install Green Dongle in top USB port (this is stored in the aluminum box taped to the top of the computer – do NOT lose this green dongle!)
    2. Power cable to INNOVA 1412 ➔ Power strip
    3. Power cable to INNOVA 1303➔Power strip
    4. Power cable to Computer➔ Power strip
    5. Doser to Analyzer tube from INNOVA 1303 Sampler “Outlet to Analyzer” to “Air Filter” on INNOVA 1412
    6. IEEE-488 cable from INNOVA 1412 ➔ INNOVA 1303

7. RS-232 through blue converter to USB on computer

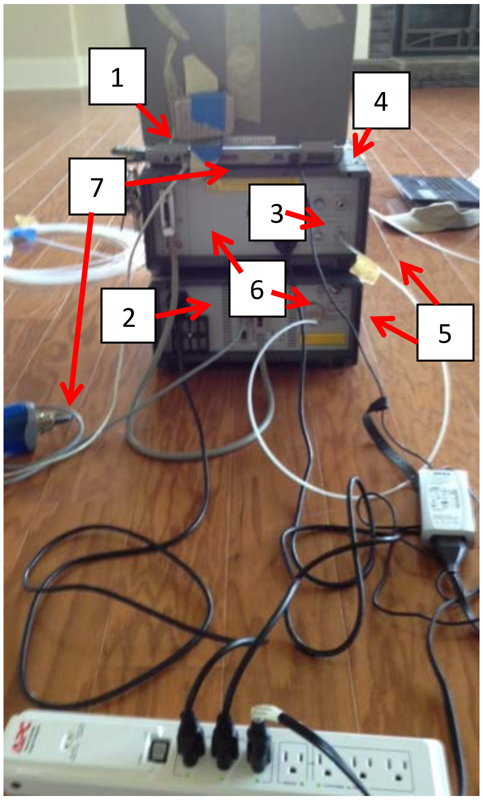


Figure C.2: Equipmet Set-up Rear View

- Once all connections are made and checked, insure that power switch on both INNOVA's are "Off" / "O"
- Plug in power strip to wall outlet.
- Turn on INNOVA's by switching both power switches from "O" ➔ "-"
- String tubing to appropriate zones and install in front of INNOVA 1303 Sampler channel
    - o Be careful not to kink the tubing
    - o Be careful of trip hazard in stringing tubing
- Channels:

    Sampler:

    1 - Living Room/1st Floor

2 - 2nd Floor

3 -Garage

4 - Attic

5 - Crawlspace

INNOVA Start-up:

- On computer desktop, open INNOVA “Shortcut to w7620.exe”
- File ➔ Open (See Figure C.3)
    - Open database – Database type – Monitoring circle
    - Select appropriate database, i.e. ZEB3_IAQ

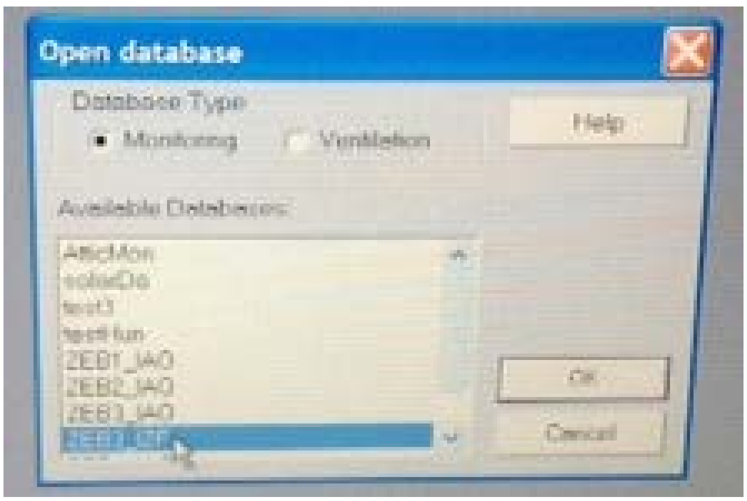


Figure C.3: Screenshot – Database Selection

    - OK

- Set-up ➔”Monitor” to set gases (See Figure C.4)
    - Compensation:
        - Ck Water Compensation, and
        - Ck Cross Compensation checked
    - Sample information – Sample Continuity checked
    - Normalization Temperature 293.15 K
    - Pressure: 101.30 kPa

- Filters
  - Ck A: FREONR134a m.w. 102.03
  - Ck B: FREONR113   m.w. 187.38 (cross compensates r134a
  - Ck W: Water Vapor
  - Other gases not checked unless using them

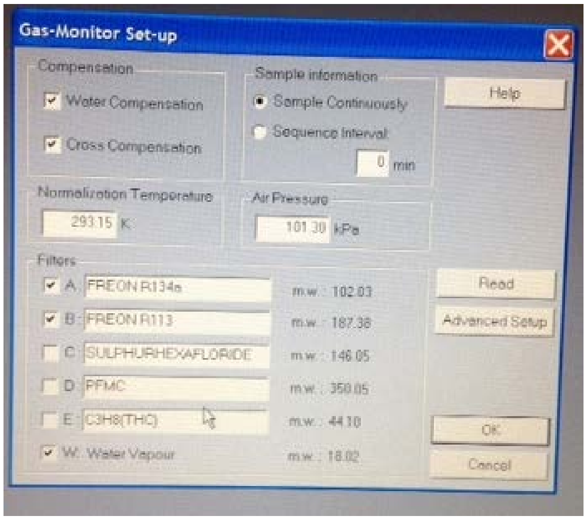


Figure C.4: Screenshot of Gas Settings

- OK

- Set-up ➔ Multiplexer (See Figure C.5)
  - Check that active channels are checked and labeled correctly
    - AER 1st Floor (1); 2nd Floor (2)
    - IZF – relevant channels 1st Floor (1); 2nd Floor (2); Garage (3); Attic (4); Crawlspace (5)

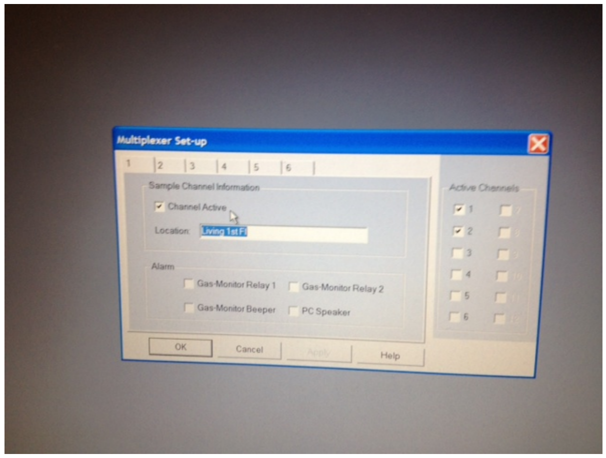


Figure C.5: Screenshot of Multiplexer Settings

- o Click OK

N.B. In Set-up, only change Monitor and Multiplexer

- View: Open 3 windows and arrange on screen. See Figure C.6.
    - o Graphic Window – top ½ of screen
    - o Numeric Window – bottom left ¼ of screen
    - o Status Window – bottom right ¼ of screen

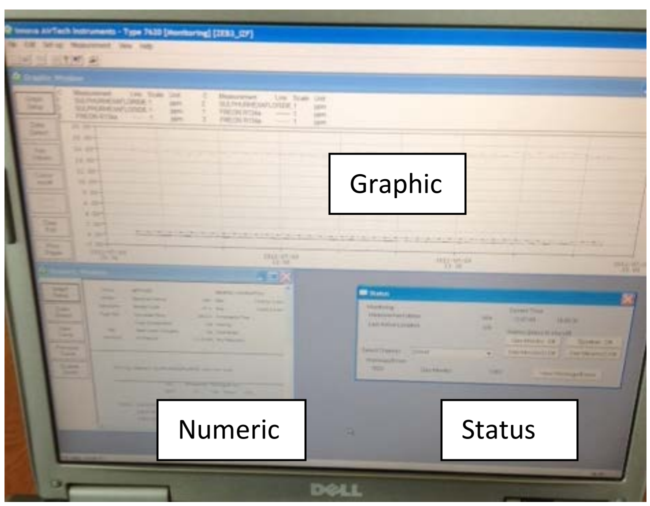


Figure C.6: Screenshot of Graphic, Numeric and Status Windows

- On Graphic Window (See Figure C.7):
    - Select “Graph Setup” on left side and set X-interval “From” and “To” Dates and Time
    - OK

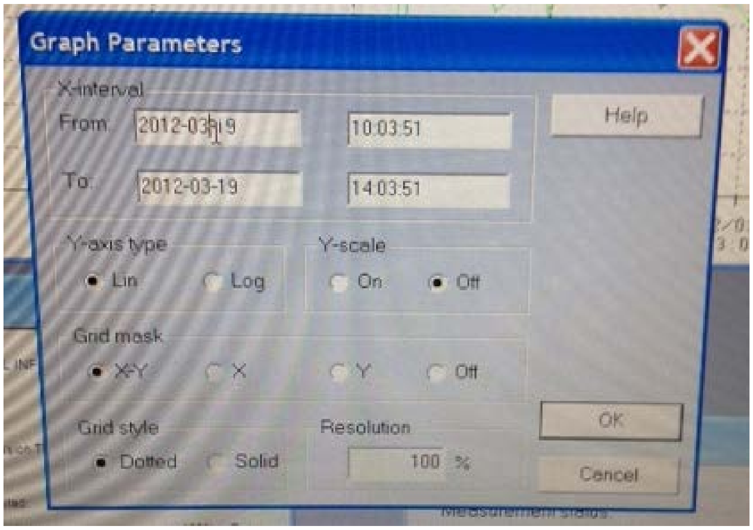


Figure C.7: Screenshot of Graph Parameters Window

    - Select “Data Select”
        - Select what data to show on the graph (See Figure C.8)

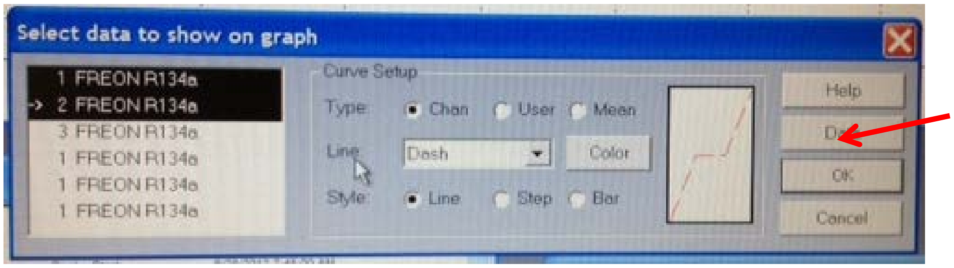


Figure C.8: Screenshot of Gas Channels to Display

            - Double click to highlight channel desired, move to next channel & double click to highlight

    - Click on “Data” Button to set-up <u>each</u> channel to be tracked on graph
    - Channel Data (set for each channel) – See Figure C.9.
        - Set Channel (1 or 2)
        - Set appropriate filter: A r134a; B R112; C SF6

          Note: for AER use r134a due to lower costs and lower Global Warming impact.

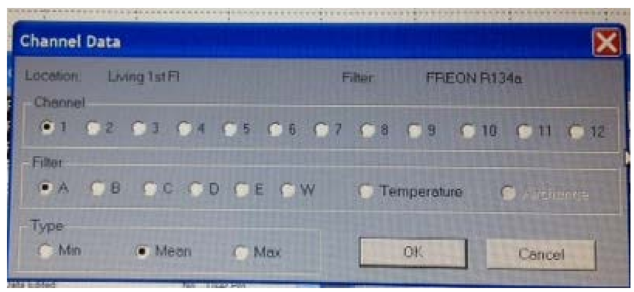


Figure C.9: Screenshot of Channel Data

    - OK on Channel Data window
    - Make sure desired channels are highlighted in black on “Select data to show on graph” window
    - OK on “Select data to show on graph” window

- Disperse tracer gas:
    - **Option A:** Using a cylinder of R134a
        - Disperse R134a by opening value as little as possible to permit a small amount of gas flow. Walk around the house to get reasonably uniform dispersion of tracer gas. Keep main blower fan on to continue mixing gas.
    - **Option B:** Using Teflon bags for a more quantitative release of gas.

- Fill 1 L Teflon bags with tracer gas. See dosing volume calculation in Tables C.1 and C.2)
- Walk around the house with bags of tracer gas with valve open and gentle pressure on the bags to distribute the tracer gas throughout the house
- While this approach does not provide as uniform dispersion as the cylinder approach, it does provide a more quantitative dispersal of tracer gas and is preferred for expensive tracer gases (i.e. SF6).

- Target tracer gas concentration is 3-4 ppm (3000 to 4000 ppb)
- Minimum detection limits:
  - r134a: 10 ppb
  - SF6: 11 ppb

Table C.1: Dosing Volumes of Tracer Gas

Dosing Volume in liters to obtain 4000 ppb			
	House 1&2	House 2&3	
Volume	1280	925	m3
	1280000	925000	L
Desired ppb	4000	4000	←Input
Required Vol of Tracer Gas	5.12	3.7	L

- To calculate other concentrations or convert units, an Excel sheet is used. An example of the Excel sheet is shown below.

Table C.2: Example of Excel Sheet for Calculation of Tracer Gas Dose

Conversion from ug/m3 to ppb						
		SF6		r134a		
	MW	146.06		102.03		
	$\mu g/m^3$ ==> ppb					
	ug/m3	100	←Input →	100		
	ppb	17	ppb	24		
	Conversion:		$ug/m^3*24.1/MW = ppb$			
	ppb ==> $\mu g/m^3$					
	ppb	4000	←Input →	4000		
	ug/m3	24,242		16,934		
	Conversion:		$ppb* MW/24.1 = \mu g/m^3$			
Dosing Volume in liters to obtain 4000 ppb						
	House 1&2	House 2&3				
Volume	1280	925	m^3			
	1280000	925000	L			
Desired ppb	4000	4000	←Input			
Required Vol of Tracer Gas	5.12	3.7	L			

Tracer Gas	**IUPAC Name**	**Formula**	**CAS**	**MW**	**MDL (ppb)**
SF6	Sulfur hexafluoride	SF_6	2551-62-4	146.06	11
R134a	1,1,1,2-Tetrafluoroethane	F_3CCH_2F	811-97-2	102.03	10

- Start Measurement: Measurement➔Start (See Figure C.10)
    - o Select Immediate or delayed start

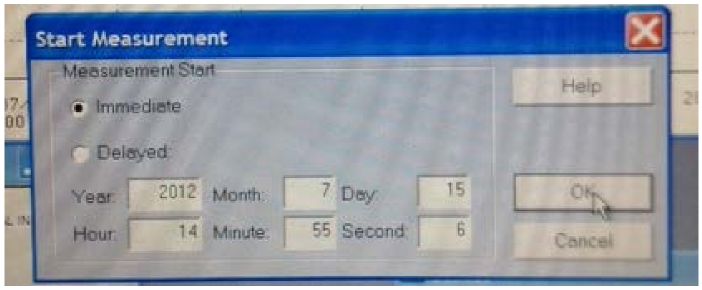


Figure C.10: Screenshot of Start Menu

- o OK

Collect >4 hours of data once 1^{st} and 2^{nd} floor curves meet (i.e. show good mixing in the space). Six (6) hours after dispersing tracer gas typically works. See ASTM E 741 for details.

Downloading the data: See Figure C.11.

1. Measurement➔Stop
    - Note: must catch this between samples, if program says "Not Responding", wait until sample is over and quickly press Measurement➔Stop
2. *File ➔ Close*
    - *Close Current Database? ➔OK*
3. *File➔Export*
    - *Export Database – Select File (i.e. ZEB3_AER)*
    - *Select channels of interest (i.e. for AER choose Channels 1 and 2)*
    - *OK*

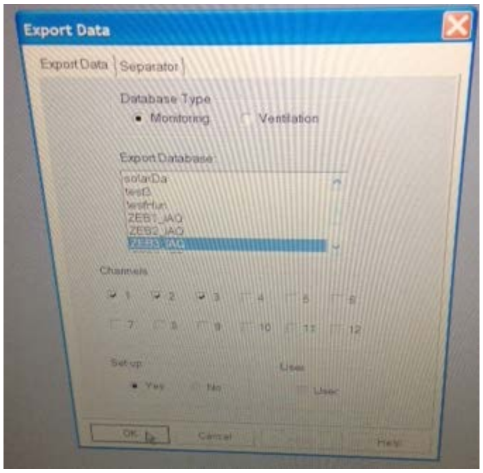


Figure C.11: Screenshot of Data Download

4. *File➔Exit - exit out of w7620*
5. *Start➔ My Computer➔Local Disk (C:)➔Program Files➔7620➔dbm➔file of interest (i.e. ZEB3_AER)*
6. *Select .txt files of channels of interest (i.e. bkmon1.txt NB: the "1" is the channel)*
   - *Look at the date of the file by sliding arrow over the file to make sure it is the date you want*
   - *Open file and then File➔ Save As➔(in removable disk USB20FD➔Data: AER:ZEB2-071312_Baseline (create other AER or IZF folders as needed)*

➔ *bkmonm1.txt*
bkmonm2.txt

Shutting Down:

- Turn off computer (Start ➔ Turn Off Computer)
  - ➔ Turn Off
- Turn off power to both Innova's (Switch power switches from "-" ➔ "O")
- Turn-off Power strip and unplug from the wall outlet

Moving to a new location:

- Computer: store green dongle in metal box taped to top of computer
- Disconnect all tubing and electrical 6 connections between INNOVA's, and computer – store in box
- Close up INNOVA's and computer
- ***MOVE ONLY ONE INNOVA unit at a time!!! These are VERY expensive pieces of equipment – carry NOTHING else when walking to the next location and pay attention so as not to fall, drop, bump, etc. the equipment. [Carrying one at a time reduces the risk of an accident and reduces the amount of damage if there is an accident.] IF any rain, cover INNOVA units in plastic when taking outside to avoid getting unit wet.***

AER Field Test Data Sheet
(One Test per Data Sheet)

Project: Optimization of Ventilation Energy Demands and Indoor Air Quality in Airtight ZEBRAlliance Homes
Sample/Intervention: ______________________________________
Sample #(s) _______
Intervention Detail: ____
[Example: 1st Floor MBRM, HEPA-60 (HEPA + 30# Carbon) attached to grille, etc.]

Site: WC___ INNOVA Location: MBRM Closet for AER
Thermostat: 1st Floor: Fan ______
Turn on INNOVA's ____
Gas Monitor Set-up ___ A R134a ____B R113; ___ C SF_6
Multiplexer Active Channels ___ 1 ___ 2 ___ 3 ___ 4 ___ 5 ___ 6

Release Tracer Gas: R134a
Sample #: _______ Released in Zones: _________ Date: ________ Time: _______
___ took canister to outside
Sample #: _______ Released in Zone: ________ Date: _______ Time:________
___ took canister to outside

INNOVA Run time:

Start: Date: _________ Time: _______ **Stop:** Date:__________ Time: ________

File name and location: (i.e. ZEB2_IAQ) __________________

File Location on USB for exported .txt files (make sure have proper date):
(Example: USB20FD →Data: AER:**ZEB2-INT4-C3a&b-092912** →bkmonm1.txt; bkmonm2.txt)

____
File location of processed data: (i.e. Data:Analysis: **WC2_AER_INT4_Oct12**)
____

Data Processing: Excel File___________________ File Location: _________________
Date File processed: ___________________

Appendix D: Air Exchange Rate (AER) Data Analysis

Air Exchange Rate (AER) Data Analysis

Reference:

ASTM, 2006, Standard E 741-00 (Reapproved 2006): Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution

Excel Spreadsheet:

Calculation of AER using Tracer Gas Data from Innova unit:

2-AER_Template-v7-R134a-112812

(E:\Data\AER\Analysis\December2011\2-AER_Template-v7-R134a-112812)

Note: a v6 for SF6 is in …Analysis\SessionA\...

Summary Sheets:

AER-Summary-Aug11-Mar12-mcj-120712 (in E:\Data\AER\Analysis\)

Also see: 1-AER-Summary-SessionA-July2012
(in E:\Data\AER\Analysis\SessionA\)

And similar files in …SessionB\ and …SessionC\

Protocol: Calculating AER (h^{-1})

- Open Excel AER_Template (most recent see above)
    - Save as a new file (i.e. AER_ZEB2_INT4-Day1-C1-092812)

- ***Open text document of AER data collected from house:***
    - From this new file: File → Open → Applicable folder (i.e. "ZEB2-INT4- C1-092812) → bkmonm1.txt (Ch 1 data) (Need to look for "<u>All Files</u>", not an Excel file). See Figure D.1.

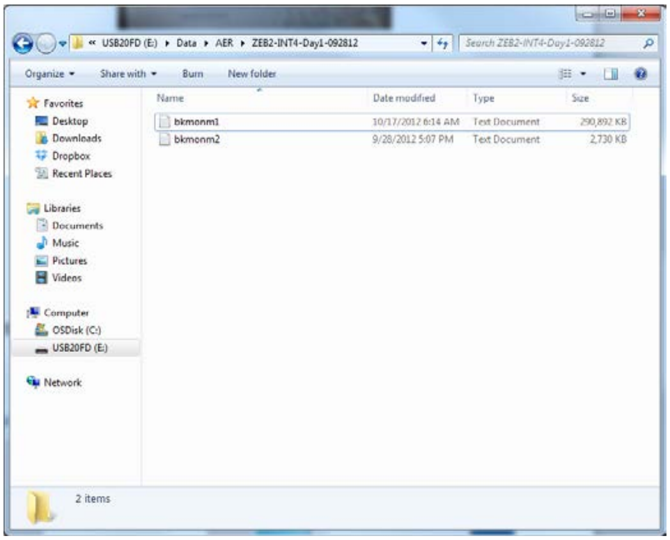


Figure D.1: Screenshot of Data File Location

    - Text Import Wizard – Step 1 of 3 – see Figure D.2

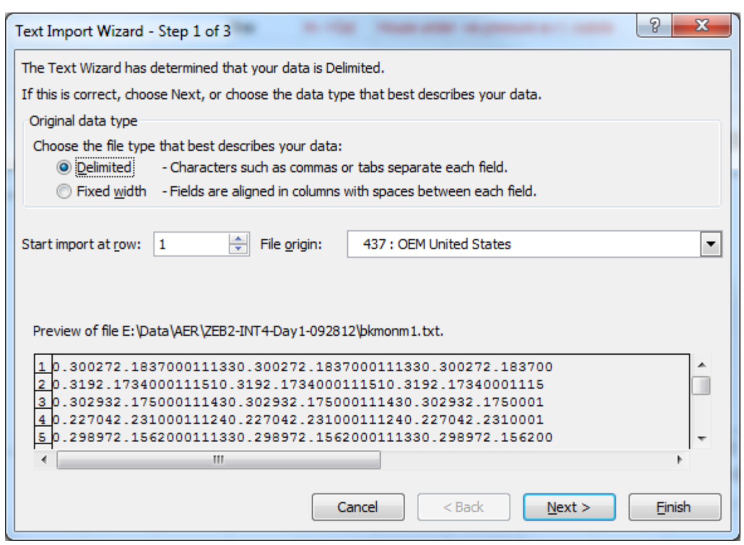


Figure D.2: Screenshot of Text Import – Step 1 of 3

- **Make sure "Delimited" is checked**
- **Start import at row: 1 – <u>or</u>, can use a row closer to start of intervention data (identified after doing a few of these) – i.e. start of INT4 in WC-2 can start import at line 12,725**
- **Hit: "Next >"**

o **Text Import Wizard – Step 2 of 3 – see Figure D.3**

- **Click on "Comma", while "Tab" box is still checked** as shown in Figure D.3

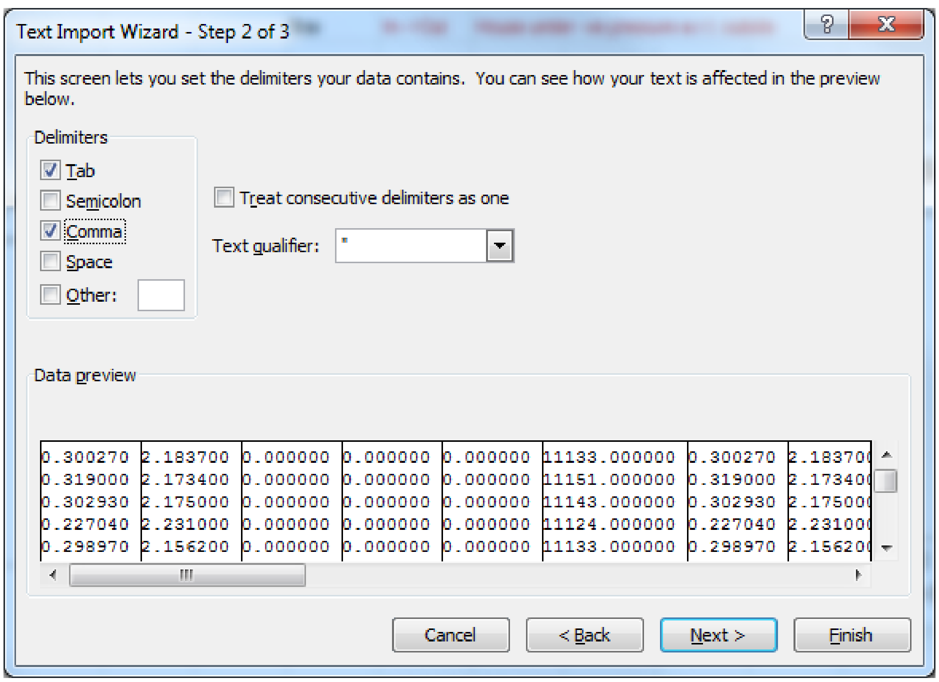


Figure D.3: Screenshot of Text Import – Step 2 of 3

- **Hit: "Next >"**

o **Temp Import Wizard Step 3 of 3 – see Figure D.4**

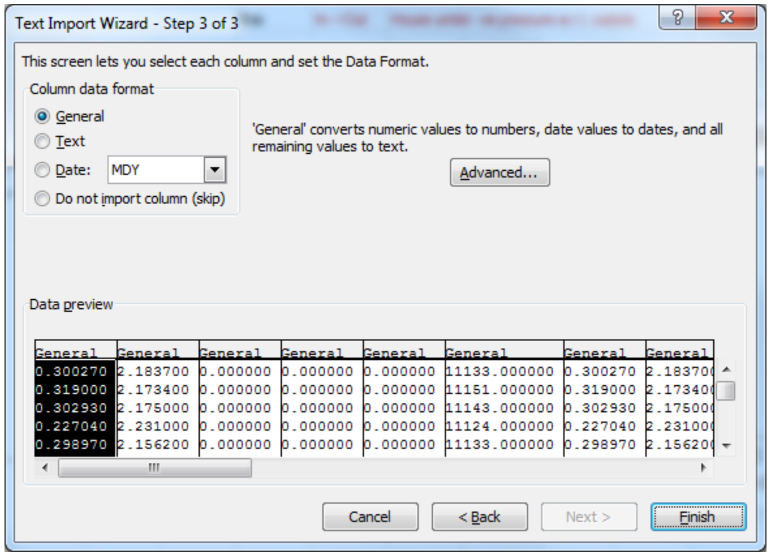


Figure D.4 Screenshot of Text Import - Step 3 of 3

- **Check that Column data format is "General"**
- **Hit "Finish"**

See example output of bkmonm1.txt file in Figure D.5.

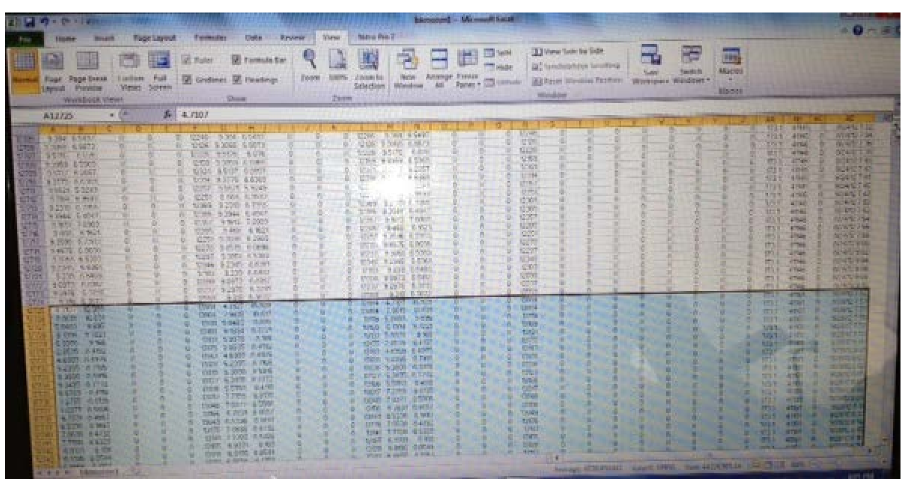


Figure D.5: Screenshot of bkmonm1.txt File

Make a new column "AD":

- Go to end of document: add column "AD" with the formula "+AB(last row)-1"
- format to - Date format: mm/dd/yy hh:mm
  - o Copy cell to top of document (Rt click, copy, place cursor on cell above (i.e. AD399), then, "CTRL"+"Shift"+ Up Arrow, then Rt click "paste"
- Select rows from 1 hour after start (to allow time for mixing) to end of Innova run time for the Sample you are working on and copy all columns for those rows. (i.e. Col A→ AD).   NB: Selecting only those cells starting 1 h after turning on the Innova to the end of the Sample you are working on is the key to making the template work.

- Insert copied cells from bkmonm1.txt (or bkmonm2.txt for 2nd floor) excel AER_Template by putting cursor on Cell F8 – rt click paste. See Figure D.6.

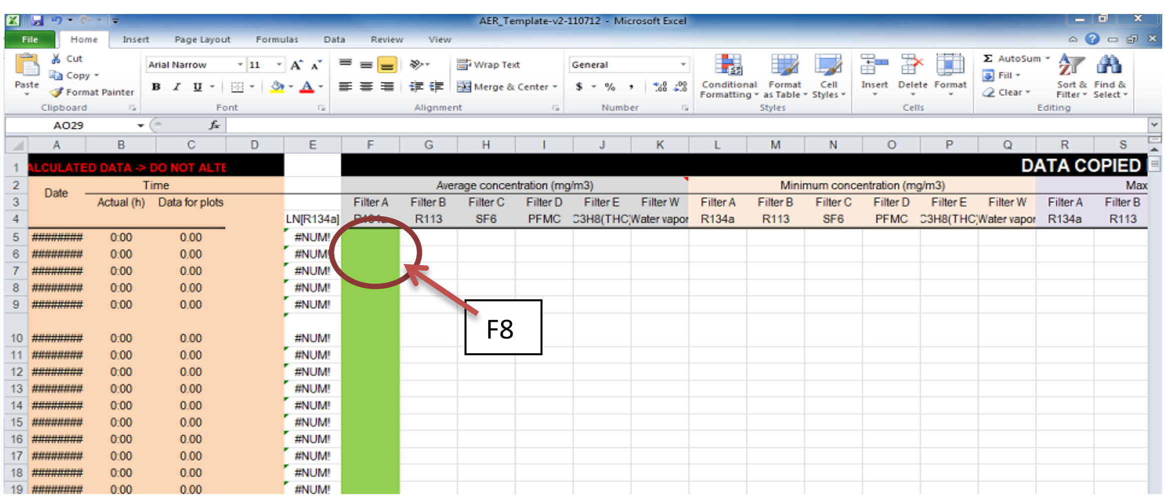


Figure D.6: Excel sheet template

- **Format Col A to fill Green to easily see [R134a] when copy into template. Start at cell F8, Ctrl/Shift/Down Arrow to get to last cell, then fill Green.**
- **Delete all rows below where Col F ([R134a]) goes below 1.0 mg/m3 – our minimum cut-off point, or rows below last data point in Col F.**
  - **Cut rows down to at least Row 2007 (needed to not impact $CONF_A$ calc.)**
  - **Remove highlighting in all cut cells to show the cut was done.**
- **<u>Record line# of last row and total hours on scratch paper</u>**
- **Repeat from *** for 2nd fl data opening bkmonm2.txt**
  - **When working on 2nd fl, delete row below 1.0 mg/m3 and then check that have same number of rows on 1st fl data. <u>IF not, delete extra rows in either 1st or 2nd floor data to get the same number of rows</u>.**
- **Close both bkmonm1.txt and bkmonm2.txt files to avoid confusion on next set of AER data. DO NOT SAVE modified bkmonm?.txt files so that original, unmodified, data will be retained in case it is needed later.**
- **<u>Record the following 1st & 2nd fl data in Summary Sheet:</u>**
  - **<u>analysis Start Time (A8:B8)</u>**
  - **<u>analysis Stop Time (Annn:Bnnn)</u>**
  - **<u>Initial & final [R134a] (F8 and Fnnn)</u>**
  - **<u>Duration of Measurement (Total Time in h) recorded on scratch paper above</u>**

Check: Both Sheets – Do 1st floor 1st, then 2nd floor:

- **Test Name: highlight in Green when correct**
- **Intervention Name and conditions:**
    - **Check that house volume is correct: (note: errors made earlier corrected in summary "Emission Rate" tab of Summary sheet)**
        - **WC1&2 45,200 ft^3 (1,280 m^3)**
        - **WC3&4 32,700 ft^3, (926 m^3)**
    - **Fan ON/OFF**
    - **Intake ERV Sealed Closed (WC2) or OA sealed closed (WC3)**
    - **Blower ON/OFF**
    - **Attached: to Window**
    - **Direction of Flow: In→Out, OR, Out→IN House under -ve/+ve pressure w.r.t outside**
    - **When all of these have been checked, highlight Intervention label (AL10LAN10) in Green**
- **Enter Sampling time (AU8) - get sampling time from last cell in Col C**
- **Enter # Last row of data (AY7)**
- **Put AER (absolute value of slope) into appropriate cell 1st floor (BA9); 2nd floor (BA12)**
- **Enter R^2 from graph into cell 1st floor (BD9); 2nd floor (BD12)**
- **Put Intercept, b into cell BA17**
- **Put in correct range (Fnnn:Fnnn) for Avg. of last 10 Pts: AL31**
- **Put in correct range (Fnnn:Fnnn) for Std Dev of last 10 Pts: AL32**
- **Check that cut-off criteria are satisfied**
    - **Last data point in Col F [R134a] >= 1.0 mg/m^3, and**
    - **SD as a % of avg of last 10 readings <10% - IF do not meet, calculate for 2nd to last set of 10 readings and try again.**

- **LINEST is optional – CONF$_{A\text{-}comb}$ is preferred as it gives the variation including mixing between floors.**
- **IF LINEST is used, function can provide more statistics on AER (Cells AL41:AL43)**
    - **Select all 3 cells**
    - **Delete original equation (can't modify a portion of a matrix)**
    - **Cells AL41:AL43: @LINEST(E8:Ennn,C8:Cnnn,,TRUE) - nnn is last line # of data**
        - **F2, then CTRL/SHIFT/Enter**
        - **3 cells will return Slope, Std. Error and R^2**
            - **value is Std. Error which shows how many sig digs can be used**

Perform above checks for both 1st floor and 2nd floor sheets, then:

- **Check that Uniformity of Concentration between 1st & 2nd floor check (0.9 <$C_{1st\ fl}$, $C_{2nd\ fl}$ < 1.1) is met → cells AR36:AS37 on 1st fl sheet are all green. IF NOT green, uniformity has not been met.**
- **Record data in Summary sheet**

To save time when CONF$_{A\text{-}comb}$ values are being calculated, only the following are saved in the summary sheet:

- **Uniformity of Conc Check 1st and last 10 pts for 1st and 2nd floors**
- **Cut-off criteria met (when tracer gas <1 mg/m^3 don't use the data)**
- **Coef of Variation for 1st and last 10 pts for 1st and 2nd floors**

(note: all additional data can be retrieved if desired later, but the goal is to get: AER, CONF$_{A\text{-}comb}$, and R^2)

To obtain an accurate $CONF_{A\text{-}Comb}$ (Confidence limits on AER of 1st and 2nd floor combined) for the combination of the 1st and 2nd floor, need to do graphically (taking least squares of $CONF_A$ does not work as the data from the 1st and 2nd floors is not independent).

- **Save current sheet! This provides data that cut-off criteria are satisfied for each set (1st fl and 2nd fl) of data before combining the data.**
- **Save data sheet as a combination sheet, i.e. with format: AER_ZEB-INT2-Day2-B2b-081012-comb**
- **In this new sheet, copy all rows starting with 8 to end of 2nd fl data and paste immediately after last row of 1st fl data on 1st fl data sheet**
- **Highlight rows A:B of the 1st row of 2nd fl data on 1st fl data sheet and add a comment "start of 2nd fl data"**
- **Check # of new last row of data and enter that into AY7 - note the # of data points in AY8 will be twice what it was previously.**
- **Note:**
  - **Ignore anything in Cols AK: BE and BL:BO below row 80 (i.e. graph copied from 2nd fl data) – ignoring this saves the time of deleting it**
  - **Data in Cols BF:BJ is needed for calculation of $CONF_{A\text{-}comb}$+/-"**
- **Change the label in BA8 from "$CONF_A$+/-" to "$CONF_{A\text{-}comb}$+/-"**
  - **For reworked data sets (ones that used a template prior to v5):**
    - **Change label in BF5 as well**
    - **Add BA20: "$CONF_{A\text{-}comb}$+/-"**
    - **Add BB20: "as% of AER"**
    - **Add BC20: "+BB9/BA9" and format to Percent with 2 dec pts**

            - **The circular reference is the label name for the test copied from the 2nd fl data and inserted in Col AL which we are ignoring – ignore this – this was corrected in v5 by moving the label to AL7 rather than AL8 so it will not be copied**

- **On graph, Rt click, Select Data and make sure starting row is correct <u>[A change will only be needed if top rows in 1st fl had to be removed</u> (i.e. row 8:xx) to achieve the cut-off criteria above]**
    - **Two sets of data that are basically parallel (1st fl and 2nd fl data) will appear on the graph. The separate between these two lines (Y-axis) is a measure of how well mixed the air is between the 1st and 2nd floor (Uniformity of Concentration). IF the uniformity of concentration is more than 10% off, boxes AS36:AT37 will be red as will have been seen above. The $CONF_{A\text{-}comb}$ value will provide a metric of the total confidence limits, including mixing (value may be less than magnitude of uniformity check).**
- **Write new AER, R2 and b from chart into cells AZ9, BB9, and BB17 respectively**
    - **When these three have been entered, put a "1" in cell BB22. Gold will appear in Cells BA9:BC9 and BC20 which are the only values that need to be added to summary sheet from the $CONF_{A\text{-}comb}$ sheet.**
- **Record data in Summary sheet**

Appendix E: HCHO Sampling Protocol

HCHO Sampling Prototcol

Equipment:

- DNPH tubes with KI ozone scrubbers – SKC 226-120 (www.skcinc.com)
- Tube Breaker/Capper, stainless steel, Size L, 8 and 10-mm OD tubes – SKC part no. 222-3-51 (www.skcinc.com)
- Single Adjustable Low Flow Holders, 5 to 500 mL/min – SKC part no. 224-26-01
- Pumps (WalMart Aquarium Air pump MX-1504 modified by Matrix Analytical Labs to provide suction and control flow to ~200 mL/min using a critical orifice to limit flow). Alternative variable restrictor from SKC (part no. 224-26-01) allows adjustment of flow from 0-500 mL/min using the same Matrix modified aquarium pumps.
- Bios Defender 530 l DryCal Calibrator (S/N 127510) 0-500 mL/min [Std. Vol. at 25 C and 101.3 kPa]
- ¼" OD tubing (clear acrylic) to connect to pump and ¼" ID tubing for DNPH tubes
- ¼"ID tubing (clear acrylic, or grey silicone) to connect DNPH tube to pump, calibrator and, for interstitial space between 1st & 2nd floor and wall sampling only, copper tubing
- ¼" copper tubing for interstitial space between 1st & 2nd floor and wall sampling only

Methods referenced:

Modified EPA TO-11a
EPA IP-6 Method update by SKC, 2004
EPA Method 0100

Modifications:

- The period of refrigeration can be up to 30 days as stated in EPA method 0100 vs. the 14 day maximum stated in EPA TO-11a and EPA OP-6. Samples are stored in polyethylene tubes in friction fit paint cans in a freezer. Transport to the lab (by car) in a cooler with ice packs. Store in freezer at lab until extracted using acetonitrile for HPLC analysis.
- QC samples are limited to:

- 2 “event blanks” for each series of samples/lab analysis. These are DNPH tubes that are never opened until analysis in the lab, but accompany the samples during storage and transport.
- Co-located samples are limited to a total of 8 samples throughout the Summer/Fall 2012 study.
- 1 “analytical duplicate” during each series of lab analysis series.

Pump Set-up

Modified Aquarium Air Pump MX-1504 (WalMart, Aqua Culture: 20-60 Gallon, Double Outlet Aquarium Air Pump, $10.52 on-line at http://www.walmart.com/ip/Aqua-Culture-20-60-Gallon-Double-Outlet-Aquarium-Air-Pump-1-ct/10532634). See Figure E.1.

Figure E.1: Aquarium Pump Package

Pump modified by Matrix Analytical Labs to pull a vacuum and provide a controlled flow of ~200 mL/min (+/- 50 mL/min) using a fixed orifice.

1. For Fixed restriction (orifice):
    a. Use fixed restrictor provided by Matrix that is inserted into ¾” long, ¼” OD, 0.071” ID Acrylic tubing
    b. Insert 1 ½” piece of ¼” OD grey (silicone) or clear (acrylic) tubing to connect to DNPH sample tube.
2. For variable restriction (orifice), attach ½” of ¼” OD clear tubing over either intake port of pump and connect to SKC Single Adjustable Low Flow Holders, 5 to 500 ml/min – SKC part no. 224-26-01.

Pump placement:

For room sampling:

- Place pump on solid inerts surface (i.e. marble counter top) with an accessible electrical outlet as shown in Figure E.2.

Figure E.2: Typical Placement of Sampling Pump in Kitchen/Living Room

For Garage Sampling:

- Place pump on an inverted empty (never been used) paint can to provide a stable inert surface for the pump that is off the floor as shwon in Figure E.3.

Figure E.3: Placement of Sampling Pump in Garage

For Wall Sampling:

- Place pump on an inverted empty (never been used) paint can to provide a stable inert surface for the pump that is off the floor and near access to wall probe. See Figure E.4

Figure E.4: Placement of Sampling Pump for Internal Wall Sampling

For Attic Sampling:

- Place pump on an inverted empty (never been used) paint can to provide a stable inert surface for the pump that is off the floor and near access to wall probe. Insert sampling tube through foam insulation in attic access door. Use ¼" copper tubing as needed. See Figure E.5.

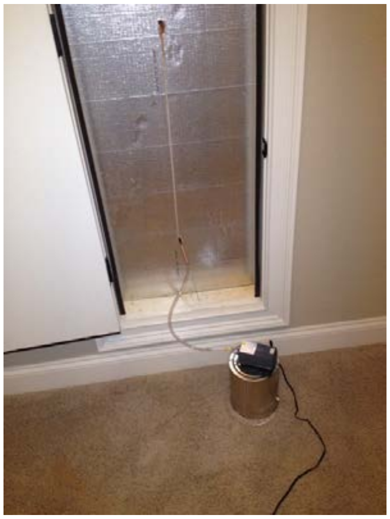


Figure E.5: Placement of Sampling Pump for Attic Sampling

For intra-floor sampling:

- Access interstitial space though drilling a hole in a supply air vent boot. See Figure E.6.

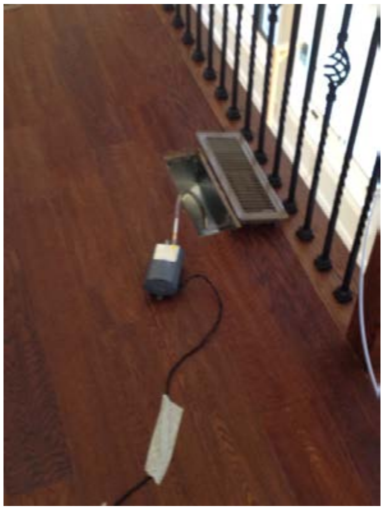


Figure E.6: Placement of Sampling Pump for Intra-floor Sampling

For crawlspace sampling:

- Place pump on an inverted, empty (never been used) paint can to provide a stable inert surface for the pump that is off the floor and near access to wall probe. See Figure E.7.

Figure E.7: Placement of Sampling Pump for Crawlspace Sampling

DNPH Tube Preparation:

- Remove tubes from freezer ~5 min prior to use to allow them to thermally equilibrate prior to attaching to pumps.
- Break off both ends of SKC 226-120 tubes using Tube Breaker/Capper, stainless steel, Size L, 8 and 10-mm OD tubes – SKC part no. 222-3-51 (www.skcinc.com)
- Insert end with DNPH into tube connected to pump (into direction of flow)

Flow Measurement:

- Turn on pump and record start date and time on DNPH Sampling Sheet.
- Attached open end of tube to Bios Defender Calibrator as shown in Figure E.8.
- Take 3 burst readings, recording each reading, average of the 3 readings (SmL/min), temperature (^{o}C)and pressure (kPa).

Figure E.8: Calibration of Flowrate through Sampling Tubes

- Record readings on sampling sheet
- Near the end of the sampling period (1h, 2h or 24 h), take a 2nd set of flow readings and record on sampling sheet

DNPH Sampling Field Test Data Sheet (One Sample per Data Sheet)

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Sample: ____
Sample #____________
Serial #, Sample #, and Site:
WC # ______ Location: ____________________________ Time check ___

Instrument: MK-1504 Pump #_____ Side: _____

Restrictor used: ___ Fixed _____ SKC Variable

Adsorbent Cartridge:

Type: SKC 225-120 LOT: ________________ Exp. __________________
Adsorbent: DNPH with KI Ozone Scrubber
Serial No. _________________________
Confirm at Stop ________________________
Both Serial No. the same? ___

Sampling Data Information: ___ Synched to start of period ____ Shinyei ______
Start Date: ________ Start Time: ______ Stop Date: _______ Stop Time:_____
Target Flowrates: ___ 24 h sample 200 cc/min; ___ 1 h sample 500 cc/min

Date	Time	1, SmL/min	2, SmL/min	3, SmL/min	Q_{avg} SmL/min	Temp, ^oC	Press, kPa

Total Time: _______min SmL Standard Conditions: T=25 ^oC; P=101.3 kPa
Comments:

Data Processing: Excel File________________ File Location: _______________
Date Entered_______________

Appendix F: Uncertainty Analysis of HCHO Measurement

Uncertainty Analysis of HCHO Measurement

Note: The greatest uncertainty is in the measurement of the mass of HCHO. The TO-11a test method (U.S. EPA, 1999) was selected to sample and analyze the air samples for HCHO as it was understood to be the "gold standard". After the field work and laboratory analysis were complete, it was discovered that the single pass (SP) DNPH derivative extraction method specified in the TO-11a method does not extract all of the derivatized DNPH. In the laboratory, this SP extraction method passes 5.0 mL of acetonitrile (MeCN) directly through the sampling tube that air was collected in during the field sampling. A more complete DNPH derivative extraction method used by Matrix Labs as recommended by Supelco (referred to as the "Shake-a-Vial" or SV extraction method) places all of the DNPH from the sampling tube in a 7 mL glass vial, adds 5.0 mL of MeCN and shakes the vial on an automated shaker for 30 minutes. An extraction procedure correction factor, f_{ext} = 1.8, was determined using nine duplicate field samples. The correction factor was then used to adjust all results obtained using the single-pass extraction as explained more fully below.

For each individual HCHO measurement, the uncertainty, ΔC of the concentration measurement, C, is determined in two ways as shown in this appendix:

Uncertainty Approach A: Error Propagation Analysis

Uncertainty Approach B: Duplicate Field Samples

The approach with the greatest uncertainty for each individual sample was used.

F.1 Uncertainty Approach A: Error Propagation Analysis

The concentration of HCHO is calculated as shown in Eqn. F.1a when the SP pass (SP) extraction procedure is used and Eqn. F.1b when the SV extraction procedure is used.

$$C_{HCHO,SP} = \frac{m * f_{ext}}{\forall} \quad \text{(F.1a)}$$

$$C_{HCHO,SV} = \frac{m}{\forall} \quad \text{(F.1b)}$$

where:

$C_{HCHO,\ SP}$ = Concentration using SP extraction procedure, µg/m^3

$C_{HCHO,\ SV}$ = Concentration using SP extraction procedure, µg/m^3

m = mass of formaldehyde collected for specific sample, µg

f_{ext} = extraction procedure correction factor = 1.8 (this is derived in

∀ = volume of air collected for specific sample, m^3

$$\Delta C = \frac{\sqrt{\left(\frac{\delta C}{\delta m}\Delta m\right)^2 + \left(\frac{\delta C}{\delta \forall}\Delta \forall\right)^2}}{1.23} \quad \text{(F.2)}$$

where:

ΔC = uncertainty in C for specific sample, ppb

Δm = uncertainty in the measurement of mass, µg

Δ∀ = uncertainty in volume of air collected, m^3

Taking the partial derivative of C with respect to m for Eqn F.1:

$$\frac{\delta C}{\delta m} = \frac{1}{\forall} \quad \text{(F.3)}$$

Rewriting Eqn F.1:

$$C = m\,\forall^{-1} \tag{F.4}$$

Taking the partial derivative of C with respect to ∀ for Eqn F.4:

$$\frac{\delta C}{\delta \forall} = -m\forall^{-2} = \frac{-m}{\forall^2} \tag{F.5}$$

Substituting Eqn (F.4) and (F.5) into Eqn (F.2):

$$\Delta C_{HCHO,ppb} = \frac{\sqrt{\left(\frac{1}{\forall}\Delta m\right)^2 + \left(\frac{-m}{\forall^2}\Delta\forall\right)^2}}{1.23} \tag{F.6a}$$

Eqn. F.6 provides the uncertainty of concentration of HCHO in ppb. The uncertainty can be reported as a % or fractionally by dividing ΔC_{HCHO} by C_{HCHO} as shown in Eqn. F.6b:

$$\Delta C_{HCHO,\%} = \frac{\Delta C_{HCHO,ppb}}{C_{HCHO}} \tag{F.6b}$$

F.1.1 Determining Uncertainty in Mass Measurement, ∆m, µg:

For each individual sample,

If Matrix' "Shake-a-Vial" (SV) extraction method was used:

$$\Delta m = m * u_{m,\,SV} \tag{F.7a}$$

If TO-11a "Single Path" (SP) extraction method was used:

$$\Delta m = m * u_{comb} \tag{F.7b}$$

where:

m = the mass of HCHO in 5 mL of acetonitrile for each specific sample, µg

$u_{m,SV}$ = fractional uncertainly of the mass measurement using the SV extraction method*

f_{exp} = extraction procedure correction factor = 1.8*

u_{comb} = combined fractional uncertainty of the mass measurement*

* These terms are derived below – all are assumed constant for all samples.

F.1.2 Combined Uncertainty of Mass Measurement, u_{comb} (used only when SP extraction was used):

When the SP extraction procedure was used on a sample, the uncertainty of the mass measurement was calculated as a combined uncertainty of the SP extraction procedure and the uncertainty of the extraction procedure correction factor, f_{ext}.

The uncertainty associated with the mass measurement of the spiked samples using the SP extraction approach, $u_{m,SP}$ and the uncertainty associated with the extraction procedure correction factor, u_{fext}, while not strictly uncorrelated, for the purposes of this calculation, they are assumed to be uncorrelated and are combined by calculating the sum of the squares of these two components of uncertainty for the mass measurement when the SP extraction procedure was used as shown in Eqn. F.8:

$$u_{comb} = \sqrt{\left(u_{m,SP}\right)^2 + \left(u_{fext}\right)^2} \tag{F.8}$$

where:

u_{comb} = combined fractional uncertainty of the mass measurement

$u_{m,SP}$ = fractional uncertainly of the mass measurement using the SP extraction method*

u_{fexp} = fractional uncertainty of extraction procedure correction factor*

* These terms are derived below – all are assumed constant for all samples.

For 68% confidence level, $u_{comb,68\%}$ = SQRT (0.014^2 + 0.12^2) = **0.12**

For 95% confidence levels, $u_{comb,95\%}$ = SQRT (0.027^2 + 0.24^2) = **0.24**

Note: the uncertainty of the extraction factor, u_{fext} dominates. Thus any correlation between the two uncertainties is insignificant.

F.1.3 Uncertainty of SP & SV Extraction Method Mass Measurement, $u_{m,SP}$ **and** $u_{m,SV}$**:**

Six sets of duplicate spiked samples were prepared at Matrix Analytical Labs using a 1000 µg/mL formaldehyde (DNPH derivative) liquid standard from Chem Service[5] and extracted with 5 mL of acetonitrile using the TO-11a “Single Pass” (SP) or Matrix/Supelco “Shake-a-Vial” (SV) extraction method as shown in Table F.1. One of the size duplicate samples was rejected based on the correction factor exceeding Chauvenet’s Criterion.

[5] Chem Service Cat No. S-12011W4-1ML; Formaldehyde (DNPH derivative) Solution F2347JS, 1000 µg/ml in Methanol:Acetonitrile (80:20) Lot No 1550800.

Table F.1: Uncertainty of Mass Measurement - Spiked (Sk) Samples

	Chauvenet's Calculation				Chauvenet's Calculation			Chauvenet's Calculation		
Spiked SP Extraction Samples	Mass HCHO in 5 mL MeCn	d_{max}	dmax / σ *	Spiked SV Extraction Samples	Mass HCHO in 5 mL MeCn	d_{max}	dmax / σ *	Factor $f_{exp,sk}$ mass SV/ mass SP	d_{max}	dmax / σ *
Sk10µg-1-1X	7.62	0.08	0.29	Sk10µg-1-SV	8.39	-0.14	-0.82	1.10	-0.03	-0.54
Sk10µg-2-1X	7.00	-0.54	-2.08	Sk10µg-2-SV	8.76	0.23	1.43	1.25	0.12	2.10
Sk10µg-3-1X	7.83	0.29	1.09	Sk10µg-3-SV	8.45	-0.08	-0.46	1.08	-0.05	-0.92
Sk10µg-4-1X	7.66	0.12	0.44	Sk10µg-4-SV	8.41	-0.12	-0.70	1.10	-0.03	-0.59
Sk10µg-5-1X	7.50	-0.04	-0.17	Sk10µg-5-SV	8.39	-0.14	-0.82	1.12	-0.01	-0.23
Sk10µg-6-1X	7.66	0.12	0.44	Sk10µg-6-SV	8.75	0.23	1.37	1.14	0.01	0.19
Trial Mean	7.55				**8.53**			**1.13**		
Trial S.D.	0.26				**0.16**			**0.06**		
n = 6	* Delete if exceeds Chauvenet's criterion for n=6; 1.73									
Mean	**7.65**							**1.11**		
S.D.	**0.11**							**0.02**		
n = 5										

* Delete data point if deviation ratio > 1.73 (n=6). Based on Chauvenet's Criterion for Rejecting Outliers ASHRAE, (2010a)

Uncertainty of the SV extraction method (n=6), u_{SV}, as a fraction is:

$$\pm 1\ \sigma,\ 68.3\%;\ u_{m,SV,68\%} = 0.16/8.53 = 0.019$$

$$\pm 1.96\ \sigma,\ 95\%;\ u_{m,SV,95\%} = 1.96 * 0.16/8.53 = 0.038$$

Uncertainty of the SP extraction method (n=5), u_{SP}, as a fraction is:

$$\pm 1\ \sigma,\ 68.3\%;\ u_{m,SP,68\%} = 0.11/7.65 = 0.014$$

$$\pm 1.96\ \sigma,\ 95\%;\ u_{m,SP,95\%} = 1.96 * 0.11/7.65 = 0.027$$

It is assumed that the uncertainty of the mass is consistent regardless of the mass collected. This is a reasonable assumption as there was <1.0% breakthrough when a 2nd DNPH tube was run in series with the initial DNPH tube (done a total of 4 times throughout the study).

An extraction procedure correction factor for the spiked samples, $f_{ext,sk}$, provides a measure of the difference of using the SV vs. the SP extraction procedure, but only for spiked samples. As shown in Table D.1, $f_{ext,sk}$ = 1.1. The uncertainty of $f_{ext,sk}$, $u_{fext,sk}$ is:

±1 σ, 68.3%; $u_{fext,sk,68\%} = 0.01/1.11 = 0.019$

±1.96 σ, 95%; $u_{fext,sk,95\%} = 1.96*0.01/1.11 = 0.038$

F.1.4 Extraction procedure correction factor, f_{ext}

This approach is used only when SP extraction was used.

When the SP extraction method was used on a sample, the calculated C_{HCHO} for that sample was multiplied by an extraction procedure correction factor, f_{ext}.

An extraction procedure correction factor, f_{ext}, was determined, as shown in Table F.2, by initially analyzing ten matched pairs of co-located field samples from a different ORNL test house. One sample of each pair was extracted using the single pass (SP or 1st Ext) extraction process recommended by EPA-TO-11a (U.S. EPA, 1999) and the other sample of the same pair was extracted using the SV extraction approach recommended by Supelco and used by Matrix Labs. Field sample pair 10, was deleted based on Chauvenet's criterion for rejecting outliers as described in ASHRAE Guideline 2-2010, Engineering Analysis of Experimental Data, Section 7.5 (ASHRAE, 2010b). The final f_{ext} = 1.8 with a standard deviation, σ=0.22.

Table F.2: Extraction Procedure Correction Factor, f_{ext}

		C_{HCHO}, ppb			Extraction Procedure Correction Factor, f_{ext}		Deviation Ratio
Sample time (h)	Field Sample	1st Ext	SV		SV Ext / 1st Ext	d_{max}	dmax / σ *
4	10	0.30	0.94		3.13	1.17	2.13
1	8	23.1	35.7		1.55	-0.42	-0.76
1	7	20.3	41.9		2.06	0.10	0.18
1	1	23.3	42.9		1.84	-0.12	-0.22
1	6	27.6	43.7		1.58	-0.38	-0.69
1	2	27.0	49.4		1.83	-0.13	-0.24
1	5	29.3	51.2		1.75	-0.22	-0.39
1	3	25.5	57.4		2.25	0.29	0.52
9.5	9	22.2	36.8		1.66	-0.31	-0.56
14.5	4	26.8	43.1		1.61	-0.35	-0.65
	Avg 9 samples	25.01	44.68	**Mean**	**1.79**		
	σ	2.77	6.53	**Std. Dev.**	**0.22**		
				1.96σ	**0.44**		

* Delete data point if deviation ratio > 1.96 (n=10). Based on Chauvenet's Criterion for Rejecting Outliers ASHRAE, (2010a)

All reported data that used the TO-11a single pass extraction procedure has been corrected by multiplying the concentration determined with the TO-11a extraction procedure by f_{ext} = 1.8.

The uncertainty of f_{ext}, u_{fext}, as a fraction is:

$$\pm 1\ \sigma,\ 68.3\%;\ u_{fext,68\%} = 0.22/1.79 = 0.12$$

$$\pm 1.96\ \sigma,\ 95\%;\ u_{fext,95\%} = 0.44/1.79 = 0.24$$

The extraction method correction factor derived using the laboratory samples that were spiked with 10 µg of formaldehyde (DNPH derivative) in methanol $f_{ext,sk}$ = 1.1 as shown in Table D.1, is much smaller than the correction factor f_{ext} =1.8 derived using nine matched field samples as shown in Table D.2. This difference may be due to the fact that the field samples adsorbed formaldehyde in a gaseous state in the duplicate field samples rather than from a liquid standard in the samples that were spiked in the lab. The difference may also be due to the range of mass seen in the field samples (1.4 – 9.1 µg on the SV extractions) compared to 8.4-8.8 µg recovered per sample on the SV extractions of the 10 µg the lab samples were spiked with. The conservative f_{ext} = 1.8 is used.

F.1.5 Determining Uncertainty in volume of air collected, ∆∀, m³:

The volume of air collected is calculated as shown in Eqn. F.9.

$$\forall = Qt \qquad \text{(F.9)}$$

where:

$\forall$ = volume of air collected, m^3

Q = volumetric flow rate, m^3/min

t = time, min

The uncertainty of the volume of air collected is calculated as shown in Eqn. F.10.

$$\Delta\forall = \sqrt{\left(\frac{\delta\forall}{\delta Q}\Delta Q\right)^2 + \left(\frac{\delta\forall}{\delta t}\Delta t\right)^2} \qquad \text{(F.10)}$$

Taking the partial derivative of ∀ with respect to t of Eqn F.9,

$$\frac{\delta\forall}{\delta t} = Q \qquad \text{(F.11)}$$

Taking the partial derivative of ∀ with respect to Q of Eqn F.9:

$$\frac{\delta \forall}{\delta Q} = t \tag{F.12}$$

Substituting Eqns F.11 and F.12 into Eqn F.10:

$$\Delta\forall = \sqrt{(t\Delta Q)^2 + (Q\Delta t)^2} \tag{F.13}$$

where:

$\Delta\forall$ = uncertainty in volume of air collected, m^3

t = sample collection time of specific sample, min

ΔQ = uncertainty in flow rate of measurement, m^3/min

Q = flow rate of specific sample, m^3/min

Δt = uncertainty in time measurement, min

Sample Collection Time, t, min:

Sample collection time was measured by a watch and is reported to the nearest whole minute. This was recorded for each specific sample.

Uncertainty in time measurement, Δt, min:

Time was measured using a digital watch that read to the nearest second. The time was recorded to the nearest whole minute and was typically within 5-10 s of the whole minute. As a worst case, the uncertainty in the time measurement is taken as 30 seconds = 0.5 min. With the shortest sample time being 60 minutes, this leads to <1% uncertainty in the time measurement.

Sample Flow Rate, Q, m^3/min:

Flow rate through the DNPH collection tube was measured at the beginning and end of the sample (using the average of three consecutive measurements) using a Bios Defender™ 530L[6] positive displacement standardized gas flow meter. The flowrate, Q in Eqn. F.12 is equal to the average flow rate, Q_{avg}, of the initial and final flow rates which are each the average of three separate Bios Defender™ readings as shown in Eqn. F.14.

$$Q = Q_{avg} = \frac{\left[\sum_{i=1}^{3} Q_i + \sum_{f=1}^{3} Q_f\right]}{2} \qquad \text{(F.14)}$$

where,

Q = sample flow rate, m^3/min

Q_{avg} = average of initial and final flow rates, m^3/min

Q_i = initial flow rate, m^3/min

Q_f = final flow rate, m^3/min

Uncertainty in flow rate measurement, ΔQ, m^3/min:

The flow meter has a range of 5-500 cc/min with a standardized accuracy of ΔQ_{meter} of 1.2% with a confidence level of 95.5%[7]

The absolute % difference (reported as a fraction), %Diff between the final and initial sample times the average flow rate as shown in Eqn. F.15

$$\%Diff = \frac{|Q_f - Q_i|}{Q_f} \qquad \text{(F.15)}$$

[6] Bios Denfender™ 530L (S/N 127510, calibrated 6/12/12 cert #512595), www.mesalab.com ,

[7] 95.5% confidence levels of standardized accuracy, e-mail from Mohammed Aziz, asim@biosint.com 6/28/13.

0The stability of flow during the sampling period, ΔQ_{flow} is calculated for each sample as shown in Eqn, F.16.

$$\Delta Q_{flow} = \%Diff * Q_{avg} \tag{F.16}$$

The error associated with the flow measurement and the error associated with the stability of the flow during the measurement are assumed to be uncorrelated and are combined by calculating the sum of the squares of these two components of uncertainty for the flow rate as shown in Eqn. F.17

$$\Delta Q = \sqrt{(\Delta Q_{meter})^2 + (\Delta Q_{flow})^2} \tag{F.17}$$

where:

ΔQ_{meter} = error associated with the flow measurement

ΔQ_{meter} = error associated with with the stability of the flow

$\Delta Q_{meter} = Q_{avg} * 0.012$, m^3/min

Q_{avg} = average flow, m^3/min

ΔQflow = error associated with stability of the flow during the sampling period

%Diff = absolute % difference between the final and initial flowrate, fractional

F.2 Uncertainty Approach B: Duplicate Field Samples

An alternate approach to calculating uncertainty is the use of duplicate field samples.

F.2.1 For samples using the SP extraction method:

To corroborate the uncertainty derived above, nine duplicate pairs of 24-hour field samples collected over the course of the study and analyzed using the TO-11a, SP extraction method were corrected using the extraction procedure correction factor, f_{ext}=1.8. As shown below in Table F.3, the overall fractional uncertainty of the measurements at 68.3% and 95% confidence levels, $u_{68\%}$ and $u_{95\%}$ are 0.14 and 0.28 respectively. These values are compared to those calculated using the uncertainty approach A. The larger uncertainty is used.

Table F.3: Uncertainty of C_{HCHO} using SP Extraction Method.

24 hour sample Field Duplicates						
			Chauvenet's Criteria Calculation			
Field Duplicate pair	$C_{HCHO,avg}$ ppb*	Std. Dev.* ppb	Uncertainty, $u_{68\%}$ as a fraction	Uncertainty, $u_{95\%}$ as a fraction	d_{max}	**dmax / σ ****
A	18	0	0	0	-1.1	-0.44
B	33	18	0.86	1.68	0.58	0.23
C	1	0	0	0	-1.1	-0.44
D	3	0	0	0	-1.1	-0.44
E	45	49	4.75	9.31	8.2	3.25
F	26	0	0	0	-1.1	-0.44
G	46	12	0.3	0.59	-0.51	-0.2
H	64	1	0.02	0.04	-1.07	-0.42
I	97	18	0.16	0.32	-0.79	-0.31
J	159	6	0.04	0.08	-1.02	-0.41
K	62	4	0.06	0.13	-0.98	-0.39
		Trial Mean	0.56	1.10		
		Trial S.D.	1.35	2.64		
		n=11				
		Mean	**0.14**	**0.28**		
		Std. Dev.	0.26	0.50		
		n = 10				

* Corrected 1st ext procedure results by multiplying by f_{ext} = 1.8
** Delete data point if deviation ratio > 2.01 (n=11). Based on Chauvenet's Criterion for Rejecting Outliers ASHRAE, (2010a)

F.2.2 For samples using the SV extraction method:

An overall uncertainty extraction procedure correction factor, f_{ext}, was determined, as shown in Table F.4, by initially analyzing five matched pairs of co-located field samples from a different ORNL test house. Field sample pair SV-3, was deleted based on Chauvenet's criterion for rejecting outliers. As shown below in Table

D.5, the overall fractional uncertainty of the measurements at 68.3% and 95% confidence levels, $u_{68\%}$ and $u_{95\%}$ are 0.023 and 0.045 respectively. These values are compared to those calculated using the uncertainty approach A. The larger uncertainty is used.

Table F.4: Uncertainty of C_{HCHO} using SV extraction method

		Chauvenet Calculation				
Field Duplicate pair	$C_{HCHO,avg}$ ppb	Std. Dev. ppb	Uncertainty, $u_{68\%}$ as a fraction	Uncertainty, $u_{95\%}$ as a fraction	d_{max}	**dmax / σ ***
SV-A	40.2	1.8	0.045	0.088	-0.008	-0.07
SV-B	77.9	2.6	0.033	0.065	-0.030	-0.29
SV-C	39.7	6	0.151	0.296	0.201	1.92
SV-D	50.7	0.3	0.006	0.012	-0.084	-0.80
SV-E	50.3	0.4	0.008	0.016	-0.080	-0.76
		Trial Mean	0.049	0.095		
		Trial S.D.	0.053	0.105		
		n = 5				
		Mean	**0.023**	**0.045**		
		S.D.	0.017	0.033		
		n = 4				

* Delete data point if deviation ratio > 1.65 (n=5). Based on Chauvenet's Criterion for Rejecting Outliers ASHRAE, (2010a)

F.3 Sample Specific Uncertainty of C_{HCHO}

Sample specific Q_{avg}, %Diff, ΔQ_{flow}, ΔQ_{meter}, ΔQ, t, Δ∀, m, and ∀, are used to calculate the uncertainty in the concentration, ΔC, of each sample and thus provide the uncertainty assocated with each data point.

Individual uncertainties for the 17 HCHO samples used in the regression analysis for house WC-2, at the 68% confidence level using both approaches are shown in Table F.5. All of these samples used the SP extraction method and thus required the use of the extraction procedure correction factor, f_{ext} = 1.8

Table F.5: Uncertainty of C_{HCHO} used in Regression Analysis for House WC-2 – 68% Confidence Level

HCHO Sample #	CHCHO with f_{ext}	Mass of HCHO in sample m (μg)	Uncertainty of measurment of mass Δm (μg)	Volume of Air V Collected (m^3)	Uncertainty of Volume of Air V Collected Δ (m^3)	Uncertainty of C_{HCHO} ΔC_{HCHO} (ppb)	Approach A Fractional Uncertainty of $C_{HCHO, 68\%}$ (fractional)	Approach B Fractional Uncertainty of $C_{HCHO, 68\%}$ (fractional)	Greatest Uncertainty
1	33	7.2	0.87	0.180	0.035	7	**0.23**	0.14	0.23
A006	74	32.8	3.94	0.362	0.005	9	0.12	**0.14**	0.14
A027	95	34.0	4.08	0.290	0.004	12	0.12	**0.14**	0.14
A029	86	30.5	3.66	0.287	0.004	10	0.12	**0.14**	0.14
A040	23	8.8	1.05	0.305	0.043	4	**0.18**	0.14	0.18
A043	64	23.9	2.87	0.304	0.038	11	**0.17**	0.14	0.17
A063	45	15.4	1.85	0.279	0.015	6	0.13	**0.14**	0.14
A067	49	16.5	1.98	0.276	0.021	7	0.14	**0.14**	0.14
B001	56	18.9	2.27	0.276	0.020	8	0.14	**0.14**	0.14
B010	25	8.6	1.03	0.277	0.018	3	0.14	**0.14**	0.14
B013	23	8.0	0.96	0.278	0.016	3	0.13	**0.14**	0.14
B030	56	18.9	2.27	0.276	0.020	8	0.14	**0.14**	0.14
B033	58	19.6	2.35	0.276	0.019	8	0.14	**0.14**	0.14
B050	72	23.1	2.77	0.261	0.035	13	**0.18**	0.14	0.18
B051	59	19.6	2.35	0.268	0.033	10	**0.17**	0.14	0.17
C001	61	21.5	2.57	0.287	0.004	7	0.12	**0.14**	0.14
C021	47	16.7	2.01	0.287	0.004	6	0.12	**0.14**	0.14
					Average	8	0.15	0.14	0.15

On average both approaches provide equivalent uncertainties of ~15% which is what Matrix has historically found to be the confidence level of their DNPH measurements.

Appendix G: Pre-publication draft of Shinyei Calibration Paper

The pre-publication draft was edited to fit the format used in this dissertation. The article, after further editing was published as:

Carter, E.M., Jackson, M.C., Katz, L.E., Speitel, G.E., 2013. “A Coupled Sensor-Spectrophotometric Device for Continuous Measurement of Formaldeyde in Indoor Environments.” Journal of Exposure Science and Environmental Epidemiology, 1-6.

My contribution was in test method development, securing the test chamber and DNPH air sampling equipment, reviewing test results and editing the article.

A coupled sensor-spectrophotometric device for continuous measurement of formaldehyde in indoor environments

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Keywords

formaldehyde; coupled sensor-spectrophotometric device; manufactured housing

Abstract

Despite long-standing awareness of adverse health effects associated with chronic human exposure to formaldehyde, this hazardous air pollutant remains a challenge to measure in indoor environments. Traditional analytical techniques evaluate formaldehyde concentrations over several hours to several days in a single location in a residence, making it difficult to characterize daily temporal and spatial variation in human exposure to formaldehyde. There is a need for portable, easy-to-use devices that are specific and

sensitive to gas-phase formaldehyde over short sampling periods so that dynamic processes governing the fate, transport, and potential remediation of this pollutant in indoor environments may be studied more effectively. A recently developed device couples a chemical sensor sampling element with spectrophotometric analysis for the detection and quantification of part per billion (ppb_v) gas-phase formaldehyde concentrations. This study established, for the first time, in a laboratory setting, the ability of the coupled sensor-spectrophotometric device (CSSD) to report formaldehyde concentrations accurately and continuously on a thirty-minute sampling cycle at low ppb_v concentrations previously untested for this device. Determination of the method detection limit (MDL), based on forty samples each at test concentrations of 5 and 10 ppb_v, was found to be 1.9 and 2.0 ppb_v, respectively. Performance of the CSSD was compared to the dinitrophenylhydrazine (DNPH)-derivatization method for formaldehyde concentrations ranging from 5-50 ppb_v, and a linear relationship with a coefficient of determination, R^2, of 0.983 was found between these two analytical techniques. The CSSD was then used to continuously monitor indoor formaldehyde concentrations in two manufactured mobile homes over the course of five days. During this time formaldehyde concentrations, as measured with the CSSD only, varied from 0-65 ppb_v and 80% of the time in one home and 100% of the time in the other were above the US National Institute for Occupational Safety and Health (NIOSH) chronic reference exposure level (chREL) of 16 ppb_v, which is also the level required by the U.S. Federal Emergency Management Agency (FEMA) to procure manufactured housing. Correlation between the CSSD and DNPH methods in the field awaits further study.

Introduction

Formaldehyde is one of the most pervasive and consistent pollutants in indoor environments, owing to a wide range of building materials and consumer products present indoors that emit formaldehyde and to a variety of chemical reactions that occur in indoor environments that generate formaldehyde. Chronic exposure to formaldehyde is often of greatest concern in indoor environments, where concentrations may be four to ten times greater than outdoor concentrations (O'Brien, Siraki, and Shangari, 2006), and such exposure is associated with numerous hazardous health endpoints, including decreased pulmonary function, sensory and respiratory irritation, respiratory tract pathology, increased asthma incidence and prevalence, and increased damage to immune systems (US Environmental Protection Agency, 2010). Furthermore, long-term exposure to formaldehyde is associated with lymphohematopoietic and nasopharyngeal cancers; thus, formaldehyde has been classified as a known human carcinogen by the International Agency for Research on Cancer (IARC) in 2006 (IARC, 2006) and more recently in 2010 and 2011 by the US Environmental Protection Agency (US Environmental Protection Agency, 2010) and US Department of Health and Human Services (National Toxicology Program, 2011), respectively.

Increased understanding of the health risks associated with human exposure to formaldehyde at concentrations observed in indoor environments, which may range from ~4-110 ppb_v (Offermann, 2009), and a growing trend to lower chronic recommended exposure limits have accelerated the need for analytical techniques capable of measuring ppb_v formaldehyde concentrations dynamically.

Numerous international organizations and national- or state-level governmental agencies have developed a range of recommended exposure limits for formaldehyde. For instance, following reports from the Agency for Toxic Substances and Disease Registry and the US Centers for Disease Control of high formaldehyde concentrations in manufactured (prefabricated) housing provided by the United States Federal Emergency Management Agency (FEMA) to families who were displaced by hurricanes Katrina and Rita in 2005, FEMA implemented procurement guidelines for manufacturers of mobile and manufactured housing. The guidelines require formaldehyde in all manufactured housing units to be less than the chronic recommended exposure level (chREL) set by the National Institute for Occupational Safety and Health (NIOSH) of 16 ppb_v over an eight hour period (FEMA, 2008a, 2008b). On the global scale, the World Health Organization has set a 30-minute and chronic recommended exposure limit (chREL) for formaldehyde of 81 ppb_v (WHO, 2010), which has been under consideration for twenty-five years (WHO, 1987). A summary of recommended exposure limits for non-cancer effects from various agencies in the US and around the world is presented in Table G.1:

Table G.1: Recommended exposure limits and threshold limit values for formaldehyde with respect to non-cancer health effects

Agency	Recommended Exposure Limits for Non-Cancer Health Effects [ppb_v]	Exposure Time Period
CA EPA OEHHA[1]	7.3	8-hr and chronic
France AFSSET[2]	8.1	Threshold limit
US EPA[3]	Under review	NA
US DHS FEMA[4]	16	8-hr
HK IAQ MG[5]	<24	8-hr
CA EPA ARB[6]	26	8-hr
Health Canada[7]	40	8-hr
WHO[8]	81	30 min and chronic

[1] California Environmental Protection Agency, Office of Environmental Health Hazard Assessment (CA OEHHA, 2008)
[2] French Agency for Environmental and Occupational Health Safety, AFSSET (Mandin et al., 2009)
[3] US Environmental Protection Agency
[4] US Department of Homeland Security Federal Emergency Management Agency (FEMA, 2008a, 2008b)
[5] Hong Kong Indoor Air Quality Management Group (HK IAQ MG, 2003)
[6] California Environmental Protection Agency, Air Resources Board (CA EPA Air Resources Board, 2004)
[7] Health Canada (2006)
[8] World Health Organization (WHO, 2010b)

A different set of recommended formaldehyde exposure levels has been developed to take into consideration cancer effects associated with formaldehyde exposure. Lifetime exposure levels associated with tiered estimates of cancer risk are provided in Table G.2. Only in exceptional cases can the US EPA's current E-4 level (1 in 10,000 risk level), 6.5 ppb_v, be achieved in residences. CA OEHHA's 1 in 10,000 risk level is 0.73 ppb_v which is less than typical outdoor levels (Offermann, 2009). With levels of formaldehyde in residences ranging from ~4-110 ppb_v, risk levels in homes may be greater than a 1 in 1,000 chance of incidence of cancer resulting from formaldehyde exposure over a lifetime.

Table G.2. Lifetime average formaldehyde inhalation exposure concentrations associated with cancer incidence risk levels.

	Average concentration [ppb_v] of inhalation exposure over a lifetime (70 years) associated with corresponding cancer risk level	
Risk Level	US EPA[1]	CA OEHHA[2]
E-4 (1 in 10,000)	6.5	0.73
E-5 (1 in 100,000)	0.65	0.073
E-6 (1 in 1,000,000)	0.065	0.007

[1](U.S. EPA, 2012a)
[2]California Environmental Protection Agency, Office of Environmental Health Hazard Assessment (CA OEHHA, 2008)

Traditional sampling methods for formaldehyde in indoor environments rely on pre-concentration and derivatization phases during sampling, after which the sample must undergo further preparation to be analyzed by the appropriate chromatographic or spectroscopic technique. Numerous reviews thoroughly describe *in situ* and derivatization-based sampling methods and analytical techniques or directly compare in greater detail two or more existing techniques (Hak et al., 2005; Wisthaler et al., 2008; Salthammer and Mentese, 2008; Barro, Regueriro, Llompart, and Garcia-Jares, 2009; Salthammer, Mentese, and Marutzky, 2010). Of the many techniques outlined in these studies, the DNPH method has become the accepted international standard procedure for analysis of formaldehyde in indoor air by the International Organization for Standardization and is described within the EPA method TO-11A and the ASTM D5197 for the determination of aldehydes in air. This and other derivatization methods suffer from long sampling times, typically several hours to several days, thus precluding the study of dynamic processes. In response to a need for shorter sampling times, Martos and Pawliszyn (1998) developed a method that employs derivatization of formaldehyde with *o*-(2,3,4,5,6-pentafluorobenzyl) hydroxylamine hydrochloride (PFBHA) on solid phase microextraction (SPME) fibers followed by thermal desorption onto a gas chromatograph and detection by flame ionization (FID) or electron capture (ECD). While sampling times are reduced to the range of one to ten minutes, preparation of the SPME fiber prior to sampling and subsequent GC-FID or ECD analysis extends the overall sampling time. Furthermore, this method is entirely manual, making continuous, dynamic sampling labor- and time-intensive. Accordingly, SPME-based formaldehyde monitoring has not achieved widespread use, and the need persists for sensor technology that can perform real-time measurement of formaldehyde and that is easy to transport to and use in the field.

Development of sensor-based sampling methods and analytical techniques is growing rapidly with increasing demand for such technology. Traditional real-time sensor technology employing the Hantzsch method, which relies on the quantitative transfer of formaldehyde from the gas phase to the liquid phase (Junkermann and Burger, 2006), is labor- and resource-intensive (Salthammer, Mentese, and Marutzky, 2010). Several commercially available real-time formaldehyde sensors that use either electrochemical or photoelectric photometry technologies were recently tested by the National Research Council of Canada under conditions similar to those used in this study and demonstrated good linearity, stability, and repeatability (Won, Nong, Yang, and Scheibinger, 2011; Xiao et al., 2011). However, method detection limits were not evaluated for any of these devices nor was performance evaluated at concentrations less than 10 ppb_v. Until recently, major shortcomings of real-time formaldehyde sensor technology have been high detection limits (Salthammer et al. 2010), sensitivity to relative humidity and temperature, and cost. A new chemical sensor element (Maruo, Nakamura, and Uchiyama, 2008) has demonstrated the ability to reliably report low formaldehyde concentrations in residential environments (Maruo, Yamada, Nakamura, Izumi, and Uchiyama, 2010). Sensor technology of this kind can be readily incorporated into a small, portable device. This study investigated performance, in the laboratory, of one such coupled sensor-spectrophotometric device (CSSD) at low ppb_v concentrations, particularly those below 10 ppb_v, relative to the standard DNPH-derivatization method and evaluated the method detection limit at two test concentrations for four unique devices of the same design.

The development of new formaldehyde sampling methods and analytical techniques well suited for dynamic indoor environments is of critical importance. Currently, when residential formaldehyde concentrations are reported, they represent an average value weighted over a time span of several hours to several days. For example, in two of the most recent, broad-based human exposure assessments to include formaldehyde—the US EPA National Human Exposure Assessment Survey (NHEXAS) (Gordon et al., 1999) conducted in 189 homes in Arizona and the Relationships of Indoor, Outdoor, and Personal Air (RIOPA) study conducted in 311 homes in three urban centers in the US (Weisel et al., 2005)—the formaldehyde concentrations were reported as time-weighted averages taken over a 6-7 day period and a 48-hour sampling period, respectively. The median formaldehyde concentration in the NHEXAS study and the mean formaldehyde concentration in the RIOPA study were both 17 ppb_v and 21.6 ppb_v, respectively. However, it is important to consider upper limit concentrations as well as central limit tendencies, especially in light of evidence that suggests peak exposure dose metrics are stronger than cumulative exposure dose metrics when evaluating causal associations between formaldehyde exposure and risk for certain lymphohematopoietic cancers (National

Research Council, 2011). Monitoring formaldehyde concentrations over shorter time scales would be valuable for developing a better understanding of temporal concentration variations. Small, portable, rugged devices also make it possible to monitor formaldehyde in several different locations in a home. This information would not only allow for better characterization of daily human exposure to formaldehyde, but it could also inform the timely application and installation of potential treatment strategies.

Manufactured homes are expected to exhibit higher levels of formaldehyde relative to site-built residences because of the building materials used in their manufacture (Hodgson, Rudd, Beal, and Chandra, 2000). Housing developments in the state of Texas known as "colonias" are dominated by single-family manufactured homes. These communities frequently lack safe and healthy housing (Ward and Peters, 2007), and knowledge of indoor environmental quality in these homes is completely absent. This study undertook to investigate the performance of the recently developed CSSD in the field by measuring formaldehyde concentrations in several manufactured homes in a Colonia outside of San Marcos, Texas.

Methods

Coupled Sensor-Spectrophotometric Device (CSSD) Calibration

The sensor element used in this study was designed for spectrophotometric analysis and consists of one chemically coated porous glass sheet adjacent to one non-coated glass sheet. The chemically coated glass sheet reacts with formaldehyde, producing a change in color on the glass, and when the absorbance at 410 nm is measured through both the coated and the un-coated glass sheet, the difference in absorbance is proportional to the formaldehyde concentration. Development of this sensor technology has been fully described elsewhere (Maruo, Nakamura, and Uchiyama, 2008). The CSSD (Shinyei Technology Co., Ltd; Kobe, Japan; Formaldehyde Multi-Mode Monitor) is a battery-operated unit, measuring 15 x 6 x 3 cm in size and housing both the chemical sensor element and the spectrophotometric equipment necessary to evaluate the sensor absorbance on a semi-continuous basis. Temperature and relative humidity are also monitored on a thirty-minute cycle. The data is stored in the CSSD until it can be downloaded to an available computer.

The experimental setup used to calibrate the CSSDs is illustrated in Figure G.1. A total of four CSSDs, each equipped with an individual chemical sensor element, were placed in a single, 10 L, stainless steel sampling chamber (Eagle Stainless, Warminster, PA, USA; CTH-24) into which was fed a single stream of nitrogen gas with a known formaldehyde concentration. The formaldehyde concentrations tested were 5, 10, 13, 25, and 50 ppb_v. A zero concentration case was also tested, during which time only zero grade (99.998%) nitrogen gas was fed to the sampling chamber. Each concentration was tested for 4-6 hours, corresponding to 8-12 sensor absorbance readings per monitor. The temperature in the sampling chamber during sampling was 20 ± 1°C, and the relative humidity was 50 ± 2%.

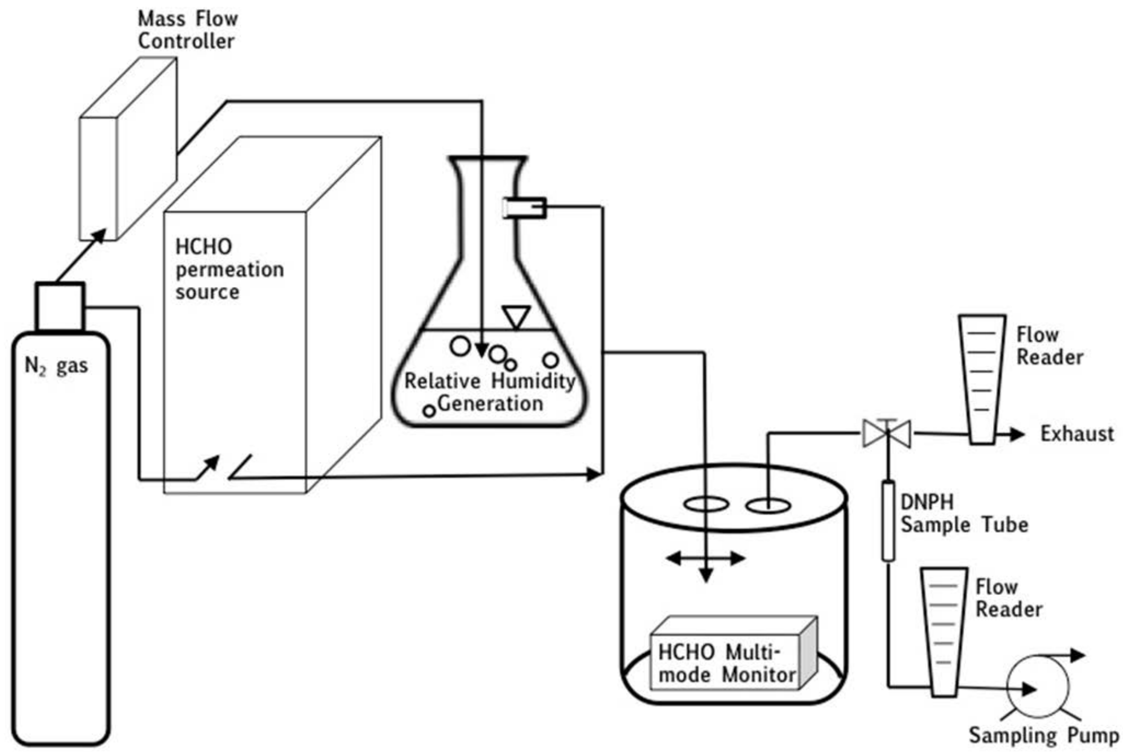

Figure G.1. Schematic of the experimental setup used to generate formaldehyde and test CSSDs.

Formaldehyde gas was generated using a Kin-Tek standard gas generator (Kin-Tek, LaMarque, TX, USA; model 491MB), which is equipped with a temperature-controlled oven to incubate a NIST-certified formaldehyde permeation tube at a specified temperature to maintain the certified emission rate. The effluent formaldehyde concentration from the standard gas generator can then be adjusted using the internal mass flow-controller to change the flow of nitrogen gas passed over the permeation source. As the flow of nitrogen increases, the concentration of the formaldehyde-laden gas stream is diluted. Two permeation sources (Kin-Tek, LaMarque, TX, USA; 33896 and 32684) with different certified emission rates were used separately to achieve the full range of concentrations tested. The permeation source with the lower emission rate was used to achieve formaldehyde concentrations below 25 ppb_v, while the permeation source with the higher emission rate was used to achieve formaldehyde concentrations of 25 ppb_v and above.

To test the performance of the formaldehyde monitors under conditions similar to actual environments, the formaldehyde gas stream was humidified to achieve a constant relative humidity of 50%. To accomplish this, nitrogen gas was regulated by a mass flow controller (Stamford, CT; Omega Engineering Inc.; FMA5514ST) before being bubbled through an Erlenmeyer flask containing de-ionized water to humidify the gas stream and subsequently combined with the formaldehyde enriched effluent from the Kin-Tek to achieve a total flow rate that corresponded to a given target formaldehyde concentration.

While continuous CSSD measurements were taken, formaldehyde samples were simultaneously collected for analysis using the DNPH-derivatization method. In accordance with the EPA TO-11A and ASTM D5197 standard procedures, DNPH-coated sorbent tubes (Eighty Four, PA, USA; SKC; 226-119), connected to an air sampling pump, actively sampled the effluent leaving the stainless steel chamber at a flow rate of 493 mL/min over the same period of time (4-6 hours) that the CSSDs were exposed to the same concentrations. Following sample collection, the sample cartridge was eluted with acetonitrile and analyzed directly with high performance liquid chromatography (Milford, MA, USA; Waters; Model 486) using a modified EPA TO-11A procedure. The eluent used was a 65/35 percent by volume acetonitrile/water solution, which was pumped (Brea, CA, USA; Beckman Instruments Inc.; 1106) at a constant flowrate of 1.5 mL/min through two

5 μm Reverse Phase C18 columns connected in series. The first column was 250 mm in length (Santa Clara, CA, USA; Agilent Technologies; Zorbaz ODS) and the second column was 150 mm in length (St. Louis, MO, USA; Supelco Analytical; LC18).

Manufactured Home Field Measurement

One CSSD was placed in each of two manufactured homes and were undisturbed for five days while they continuously measured formaldehyde concentrations in these homes. The homes were similar in size (approximately 500 m^3 in total volume), layout (3-bedroom homes of approximately 140 m^2 each) and age (each over ten years old). New sensor elements were installed in the CSSDs at the start of field sampling in the homes, and the CSSDs were placed in a common room (not a bedroom or the kitchen) at a height of approximately 1.5 m above floor level. The CSSDs were placed so as to avoid any direct contact with known sources of formaldehyde emissions (*e. g.* on top of cabinetry made from medium density fiberboard). After five days, the CSSDs were retrieved.

Results and Discussion

CSSD Calibration

Four CSSDs were used to measure six different formaldehyde concentrations continuously for four to six hours, taking an absorbance reading every thirty minutes. Performance by the four CSSDs was evaluated for equivalence using a two one-sided test (TOST) procedure. For this analysis, a (1 – 2α) 100 percent confidence interval was constructed (Huh, 1994; Barker, Luman, McCauley, and Chu, 2001), where $\alpha = 0.05$ (just as with null hypothesis difference analysis) and $z_{1-\alpha} = 1.645$. The null hypothesis for this analysis was that the CSSDs differ by at least $\Delta = \pm$ 10 percent. Thus, any two CSSDs were considered equivalent if the 90 percent confidence interval calculated for the difference between two CSSDs was contained within the interval ± 10 percent.

According to the TOST analysis, all four CSSDs were found to behave equivalently. The data from all CSSDs were then pooled to determine an average concentration over the given sampling period. Formaldehyde concentrations determined using the CSSDs were plotted versus formaldehyde concentrations determined using the DNPH-derivatization method and presented in Figure 2. The statistical analysis showed very strong agreement between the two analytical techniques with a coefficient of determination of 0.983. This result is important because it demonstrates the ability of the CSSD to match the performance of the DNPH standard procedure for formaldehyde monitoring. Of particular note, manufacturers of the CSSDs evaluated in this study have been yet unable to test performance at concentrations below 10 ppb_v and currently report a detection limit of 20 ppb_v, so this study has provided new and valuable insight into the performance of a coupled sensor and spectrophotometric device.

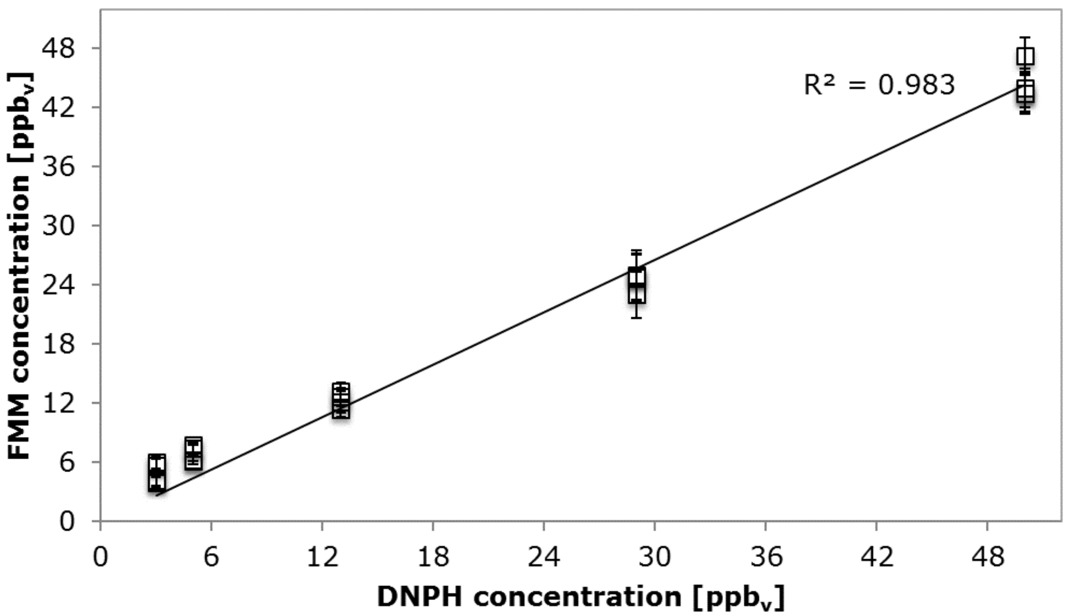

Figure G.2. Correlation between reported formaldehyde concentrations from CSSDs and the DNPH-derivatization method.

Evaluation of CSSD Method Detection Limit

The method detection limit (MDL) associated with 40 measurements taken at a 5 ppb$_v$ level by the four CSSDs was estimated as the product of the standard deviation of the 40 replicate samples at a 5 ppb level (sd_{5ppb} = 0.947) and the one-tailed *t*-statistic for *n* = 39 degrees of freedom at the 95% confidence level ($t_{(n=39,\alpha=0.95)}$ = 2.042). The estimated MDL was 1.9 ppb$_v$.

To test the robustness of the MDL estimate, the same procedure was applied at the 10 ppb$_v$ level. With sd_{10ppb} = 0.982 and $t_{(n=39,\alpha=0.95)}$ = 2.042, the estimated MDL was 2.0 ppb$_v$, suggesting that this evaluation is robust and not dependent on the initial test concentration.

Manufactured Home Field Measurement

The formaldehyde concentration data presented in Figure G.3 were obtained from continuous monitoring of two manufactured homes over the course of five days, with measurements recorded every thirty minutes. Concentrations in both homes are typically, in the case of home 2, and exclusively, in the case of home 1, above the NIOSH chREL. In fact, formaldehyde concentrations in Manufactured Home 1 are above the NIOSH chREL for the entire sampling period. In Manufactured Home 2, formaldehyde concentrations are above the NIOSH chREL 80% of the time. Even so, it is significant to consider that over the course of five days of monitoring, the formaldehyde concentrations show considerable variability. The time-weighted average formaldehyde concentrations evaluated over five days in Manufactured Homes 1 and 2 are 34.2 and 22.4 ppb_v with standard deviations of ± 6.5 and ± 10.7 ppb_v, respectively. Formaldehyde concentrations in Manufactured Home 1 ranged from 17-53 ppb_v, while those in Manufactured Home 2 ranged from 0-65 ppb_v. It was observed that Manufactured Home 1 contained more home furnishings and wood-paneled walls than did Manufactured Home 2, which might provide some explanation for the higher average formaldehyde concentration. At the same time, the higher peak formaldehyde concentrations in Manufactured Home 2 might be explained, in part, by the observation that the occupants in this home cooked meals more frequently and for longer duration than occupants of Manufactured Home 1.

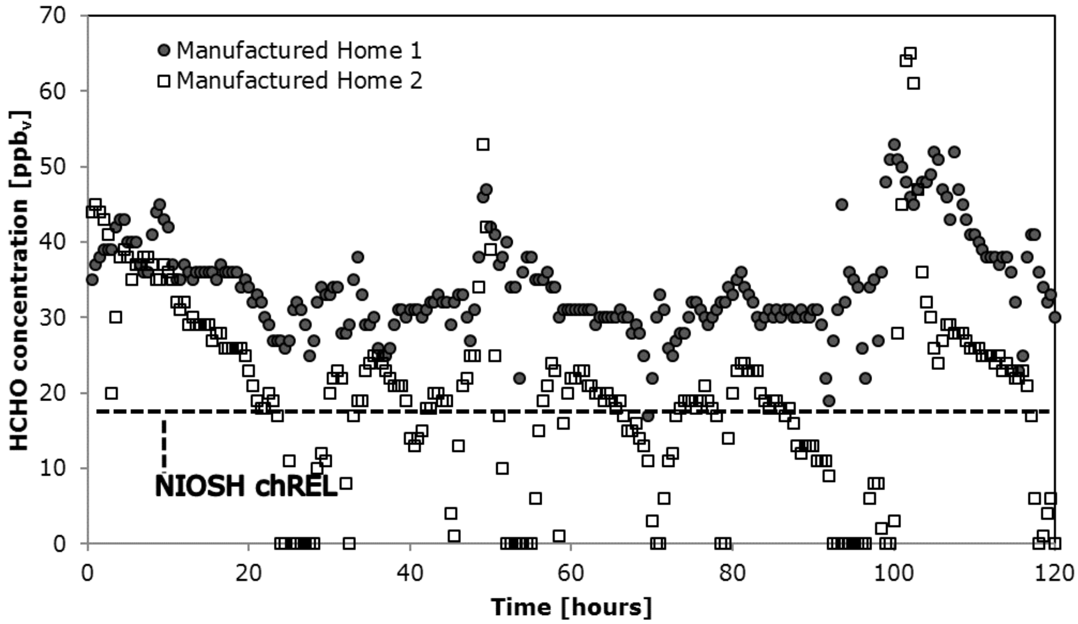

Figure G.3. Continuous formaldehyde sampling for five days in two manufactured homes in a colonia outside San Marcos, TX.

These results could have important implications for the ability to conduct dynamic formaldehyde monitoring in actual residential, commercial, and occupational environments, where previously only single, time-averaged data points could be collected. Continuous characterization of indoor formaldehyde concentrations, as has been presented here, makes it possible to correctly distinguish specific sources, internal or external environmental parameters, or specific activity patterns that may influence or exacerbate human exposure to formaldehyde indoors. Devices such as the one evaluated in this study enable researchers to quickly develop rich datasets of temporal and spatial variation in formaldehyde concentrations in a large number of homes. Taken together with housing characteristics and occupant time-activity patterns, strategies to reduce human exposure to formaldehyde, such as modifying a certain behavior or removing a specific source, can be targeted and effective.

This analytical technique also makes it possible to evaluate treatment strategies for their performance on a dynamic basis. During development of treatment materials or strategies to reduce formaldehyde exposure in indoor environments, knowledge of real-time formaldehyde concentrations upstream and downstream of a particular treatment strategy can shed light on the removal mechanisms at work, as well as the ability of a given treatment strategy to maintain formaldehyde levels below acute and chronic recommended exposure levels. Knowledge of spatial variability in indoor formaldehyde concentrations would also make it possible to target specific placement of a treatment material. Similarly, it would be possible to identify specific timing or frequency of a treatment material's use, once greater understanding of temporal variability in indoor formaldehyde concentrations is available.

This study improved understanding of a newly developed coupled sensor-spectrophotometric device (CSSD) capable of continuous measurement of gas-phase formaldehyde concentrations. The method detection limit, in a laboratory setting, for the new instrument determined in this study was shown to be competitive with the widely accepted standard method of DNPH-derivatization. Furthermore, the CSSD requires only two hours or less to report an initial 30-minute average formaldehyde concentration without additional sophisticated analysis in the laboratory on the part of the researcher. This combined sampling method and analytical technique impacts the ability of homeowners, regulators, public health investigators, and researchers to assess temporal and spatial variability of formaldehyde concentrations within a home and across a wide range of indoor environments. This capability is especially important when investigating the relative impacts of formaldehyde treatment strategies. The application of the CSSD is not intended to replace the internationally accepted DNPH-derivatization method, or other such well-established methods. However, the CSSD offers regulators, scientists, and engineers the ability to complement data from traditional analytical methods by revealing more finely resolved spatial and temporal trends in formaldehyde concentrations that inform both policy-level decisions, as well as design of appropriate treatment technology.

While this study shows great promise in measuring sub-10 ppb levels of formaldehyde in the laboratory, a limitation of this study was that DNPH samples were not obtained during field sampling. Additional study needed to obtain field correlations between the CSSD device and the DNPH-derivatization method and consistency of results in the field between CSSD units and individual sensors, particularly between sensor batches awaits further study.

Acknowledgements

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Appendix G References

Barker LE, Luman ET, McCauley MM, Chu SY. Assessing equivalence: an alternative to the use of difference tests for measuring disparities in vaccination coverage. *Amer J Epidemiol* 2002; **156** (11): 1056-1061.

Barro R, Regueriro J, Llompart M, Garcia-Jares C. Analysis of industrial contaminants in indoor air: Part 1. Volatile organic compounds, carbonyl compounds, polycyclic aromatic hydrocarbons and polychlorinated biphenyls. *J Chromatogr A* 2009; **1216**: 540-566.

CA OEHHA. Acute, 8-hour, and chronic reference exposure levels (chRELs). *Technical Support Document for Noncancer RELs, Appendix D1* 2008; California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, Air Toxicology and Epidemiology Branch, Sacramento, CA: 128-169.

CA OEHHA. Methodologies for derivation, listing of available values, and adjustments to allow for early life stage exposures. *Technical Support Document for Cancer Potency Factors. Appendix A: Hot Spots Unit Risk and Cancer Potency Values* 2009; California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, Air Toxicology and Epidemiology Branch, Sacramento, CA.

CARB. Indoor air quality guideline No.1: formaldehyde in the home. California Air Resources Board, Sacramento, CA 2004.

FEMA. FEMA response to formaldehyde in trailers (redacted). Department of Homeland Security, Office of Inspector General, Washington, DC 2008.

Gordon S, Callahan P, Nishioka M, Brinkman M, OÕRourke M, Lebowitz M, and Moschandreas D. Residential environmental measurements in the National Human Exposure Assessment Survey (NHEXAS) pilot study in Arizona:

preliminary results for pesticides and VOCs. *J Expo Anal Environ Epidemiol* 1999; **9**: 456–470.

Hak C, Pundt I, Trick S, Kern C, Platt U, Dommen J, Ordóñez C, Prévôt ASH, Junkermann W, Astorga-Lloréns C, Larsen BR, Mellqvist J, Strandberg A, Yu Y, Galle B, Kleffmann J, Lörzer JC, Braathen GO, Volkamer R. Intercomparison of four different in-situ techniques for ambient formaldehyde measurements in urban air. *Atmos Chem Phys* 2005; **5**: 2881-2900.

Health Canada. Residential indoor air quality guideline: formaldehyde. *Health Canada* 2006; **4120**, ISBN: 0-662-42661-4.

Hodgson AT, Rudd AF, Beal D, Chandra S. Volatile organic compounds concentrations and emission rates in new manufactured and site-built houses. *Indoor Air* 2000; **10**: 178-192.

HK IAQ MG. A guide on indoor air quality certification scheme for office and public places. Government of Hong Kong Special Administrative Region, Indoor Air Quality Management Group 2003.

Huh MH. Equivalence testing as an alternative to significance testing. *J Korean Stat Soc* 1994; **23**: 199–206.

International Agency for Research on Cancer. Formaldehyde. In: Formaldehyde, 2-butoxyethanol and 1-tert- butoxypropan-2-ol. *IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans* 2006; **88**: 39–325.

Junkermann W, Burger JM. A new portable instrument for continuous measurement of formaldehyde in ambient air. *J Atmos & Oceanic Tech* 2006; **23**: 38-45.

Mandin C, Bonvallot N, Kirchner S, Keirsbulck M, Alary R, Cabanes P, Dor F, LeMoullec Y, Mullot J, Peel A, Rousselle C. Development of French indoor air quality guidelines. *Clean* 2009; **37**(6): 494-499.

Martos, PA, Pawliszyn J. Sampling and determination of formaldehyde using solid-phase microextraction with on-fiber derivatization. *Anal Chem* 1998; **70**: 2311-2320.

Maruo YY, Nakamura J, Uchiyama M. Development of formaldehyde sensing element using porous glass impregnated with □-diketone. *Talanta* 2008; **74**: 1141-1147.

Maruo YY, Yamada T, Nakamura J, Izumi K, Uchiyama M. Formaldehyde measurements in residential indoor air using a developed sensor element in the Kanto area of Japan, *Indoor Air* 2010; **20**: 486-493.

National Research Council. Review of the Environmental Protection Agency's draft IRIS assessment of formaldehyde, Board on Environmental Studies and Toxicology. *The National Academies Press* 2011; Washington, DC.

National Toxicology Program. Report on Carcinogens, Twelfth Edition. U.S. Department of Health and Human Services, Public Health Service, National Toxicology Program, Research Triangle Park, NC 2011.

O'Brien PJ, Siraki AG, Shangari N. Aldehyde sources, metabolism, molecular toxicity mechanisms, and possible effects on human health. *Crit Rev Toxicol* 2005; **35**: 609-662.

Offermann FJ. Ventilation and indoor air quality in new homes. California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program. Collaborative Report. *CEC-500-2009-085* 2009.

Salthammer T, Mentese S, Marutzky R. Formaldehyde in the indoor environment. *Chem Rev* 2010; **110**: 2536-2572.

Salthammer T, Mentese S. Comparison of analytical techniques for the determination of aldehydes in test chambers, *Chemosphere* 2008; **73**: 1351-1356.

US Environmental Protection Agency. IRIS Toxicological Review of Formaldehyde (Inhalation) (External Review Draft). *EPA/635/R-10/002A* 2010; U.S. Environmental Protection Agency, Washington, DC.

US Environmental Protection Agency. Proposed guidelines for carcinogen risk assessment. *Federal Register* 1996; **61**(79): 17960-18011.

Ward PM, Peters PA. Self-help housing and informal homesteading in peri-urban America: settlement identification using digital imagery and GIS. *Habitat International* 2007; **31**: 205-218.

Weisel CP, Zhang J, Turpin BJ, Morandi MT, Colome S, Stock TH, Spektor DM, Korn L, Winer AM, Kwon J, Meng QY, Zhang L, Harrington R, Liu W, Reff A, Lee JH, Alimokhtari S, Mohan K, Shendell D, Jones J, Farrar L, Maberti S, Fan T. Relationship of Indoor, Outdoor, and Personal Air (RIOPA): Part I. collection methods and descriptive analyses. *HEI Report No. 130 (Pt. 1) NUATRC Report No. 7* 2005; Health Effects Institute, Boston, MA; National Urban Air Toxics Research Center, Houston, TX.

Wisthaler A, Apel EC, Bossmeyer J, Hansel A, Junkermann W, Koppmann R, Meier R, Müller K, Solomon SJ, Steinbrecher R, Tillmann R, Brauers T. Technical Note: Intercomparison of formaldehyde measurements at the atmosphere simulation chamber SAPHIR. *Atmos Chem Phys* 2008; **8**: 2189-2200.

Won D, Nong G, Yang W, Scheibinger H. Characterizing commercially available formaldehyde sensors. In: *Proceedings of Indoor Air 2011* 2011; a126.

World Health Organization. Air quality guidelines for Europe, Copenhagen, World Health Organization Regional Office for Europe. *WHO Regional Publications, European Series* 1987; **23**.

World Health Organization. WHO guidelines for indoor air quality: selected pollutants. The WHO Centre for Environment and Health, Bonn Office 2010.

Xiao GG, Zhang Z, Weber J, Ding H, McIntosh H, Desrosiers D, Norg G, Won DY, Dunford J, Tunney J, Darcovich K, Diaz-Quijada G. Trace amount formaldehyde gas detection for indoor air quality monitors. *NRCC-54484* 2011.

Appendix H: Model Equations, Parameters, and Validation

H.1 Model Equations

An iterative EnergyPlus™ model could be used to determine the ventilation rate or level of Gas Phase Filtration (GPF) required to achieve specific C_{HCHO} during every hour of the year for each scenario considered. Due to the large number of scenarios considered in this dissertation, a more straightforward Excel-based Formaldehyde Removal and Energy Equations (FREE) model was developed. The outputs ($T_{i,n}$, $\%RH_{i,n}$, $\lambda_{inf,n}$, $q_{house\ only,n}$) from the EnergyPlus™ runs described in the previous section are used as inputs to FREE. To compare other scenarios on a consistent basis, these $T_{i,n}$, $\%RH_{i,n}$, $\lambda_{inf,n}$, and $q_{house\ only,n}$ are used as fixed parameters for each site. These fixed parameters are used in conjunction with ventilation and GPF scenarios. Typical Meteorological Year (TMY3) climatic data ($T_{o,n}$ and $\%RH_{o,n}$) are used in the FREE model to calculate the HVAC energy required for each scenario j ($q_{j,n}$).

H.1.1 Formaldehyde Model Equations

Formaldehyde concentrations are determined using the empirical models presented in Ch 5 for houses WC-2 and WC-3 as shown in Eqns. H.1 and H.2.

$$C_{HCHO,\ WC\text{-}2,\ i,\ n} = -90.4\ \lambda_{tot} + 9.43\ T_i - 2747 \quad \text{(H.1)}$$

$$C_{HCHO,\ WC\text{-}3,\ i,\ n} = -270\ \lambda_{to} + 32.85\ T_i - 9556 \quad \text{(H.2)}$$

The correlations presented in Ch 5 were developed for Knoxville using measured indoor temperature, concentrations of formaldhyde, $C_{HCHO,i}$ and air leakage. The outdoor concentration of formaldehyde, $C_{HCHO,o}$ was assumed to be constant and 2 ppb, and all supply ventilation air was passed through a HEPA/Carbon filter to reduce the impact of any variation in $C_{HCHO,o}$.

Equation H.1 was based on measured indoor temperatures from 22.8-27.5 ^oC and total air leakage from 0.02 – 0.38 h-1. Equation H.2 was based on measured indoor temperatures from 21.7-23.6 ^oC and total air leakage from 0.1 – 0.48 h^{-1}. While these equations were used to extrapolate to higher total air leakage rates, it is noted that at ventilation rates above 0.5 -0.6 h^{-1} and T_i < ~20 ^oC, the concentration of formaldehyde becomes negative. When this occured, $C_{HCHO,i}$ was set to $C_{HCHO,o}$ as in Tables 5.1 and 5.2.

If $C_{HCHO,o}$ is different than 2 ppb and/or the GPF efficiency for HCHO, η_{HCHO} is different than 0.6, Eqns. H.1 and H.2 need to be adjusted. The incremental change in $C_{HCHO,i}$ is estimated using Eqn. H.3.

$$\Delta C_{HCHO,i,n} = C_{HCHO,o,n}\,(1-\eta_{HCHO}) \quad - \quad 2\,(1 - 0.6) \qquad (H.3)$$

$C_{HCHO,o,n}$ and η_{HCHO}
used when correlations
in Knoxville developed

The generalized form of Eqns H.1 and H.2, accounting for different $C_{HCHO,o}$ and η_{HCHO} are shown in Eqns. H.4 and H.5.

$$C_{HCHO,\ WC\text{-}2,\ i,\ n} = -90.4\ \lambda_{tot} + 9.43\ T_i - 2747 + [C_{HCHO,o,n}\ (1-\eta_{GPF}) - 0.8] \qquad (H.4)$$

$$C_{HCHO,\ WC\text{-}3,\ i,\ n} = -270\ \lambda_{tot} + 32.85\ T_i - 9556 + [C_{HCHO,o,n}\ (1-\eta_{GPF}) - 0.8]) \qquad (H.5)$$

When the total air exchange rates, λ_{tot}, required for a defined $C_{HCHO,i}$ is desired, Eqns. H.4 and H.5 can be reagganged as shown in Eqns H.6 and H.7 respectively.

$$\lambda_{tot} = [9.43\ T_i - 2747 + C_{HCHO,o,n}\ (1-\eta_{GPF}) - 0.8 - C_{HCHO,\ WC\text{-}2,\ i,\ n}]/90.4 \qquad (H.6)$$

$$\lambda_{tot} = [32.85\ T_i - 9556 + C_{HCHO,o,n}\ (1-\eta_{GPF}) - 0.8 - C_{HCHO,\ WC\text{-}2,\ i,\ n}]/270 \qquad (H.7)$$

where,

subscripts:
- H* = House:
  - WC-2 = House WC-2
  - WC-3 = House WC-3
- L = Location:
  - i = indoor
  - o = outdoor

n = hour of the year (n=1 to 8,760)

λ_{tot} = total air exchange rate, h^{-1}
$C_{HCHO, H*,L, n}$ = formaldehyde concentration, ppb
T_i = temperature, K
η_{HCHO} = HCHO removal efficiency for GPF, unitless

The effects of $C_{HCHO,o}$ on emission rates are ignored in this study. No emission effect as observed by Hult et al. (2015) was observed or accounted for in this model. In this dissertation, outdoor concentrations of formaldehyde at any site are considered to be constant throughout the year.

H.1.2 Superposition of Natural and Mechanical Ventilation

Superposition is how balanced and unbalanced ventilation are combined. The total air exchange rate for the house (λ_{tot}) includes all ventilation: natural infiltration (λ_{inf}), unbalanced (supply or exhaust) mechanical ventilation ($\lambda_{u,v}$), unbalanced duct leakage (the difference between supply and return duct leakage) ($\lambda_{u,l}$), and balanced (energy recovery ventilator) mechanical ventilation ($\lambda_{b,v}$). Combining mechanical and natural ventilation can be complex. Unbalanced mechanical ventilation (supply or exhaust) can change the internal pressure of the space. When the pressure of the space is changed, the infiltration rate can change. There are many approaches to account for this effect as described by Hurel et al. (2015).

In order to reduce the complexity of detailed calculations of pressure differentials and mass transfer using first principles, ASHRAE 62.2-2013, EnergyPlus™ v.7.2.0.006 and FREE rely on simplified superposition models that approximate total ventilation. To define the amount of mechanical ventilation required, ASHRAE 62.2-2013 uses a simple additivity model to combine natural infiltration and mechanical ventilation as shown in terms of air exchange rate in Eq. H.8 (ASHRAE, 2013b).

$$\lambda_{fan} = \lambda_{tot} - \lambda_{inf} \tag{H.8}$$

where,

subscripts:

$_{inf}$ = infiltration

$_{fan}$ = ventilation from a fan / mechanical ventilation

$_{tot}$ = total ventilation

λ = air exchange rate, h^{-1}

In the FREE model, the total air exchange rate is calculated using the Walker & Wilson (1998) infiltration model using quadrature as done in EnergyPlus™ (EnergyPlus(TM), 2012), as shown in Eq. H.9 with units of h^{-1}. Note that only unbalanced components of ventilation (infiltration, unbalanced mechanical ventilation, and unbalanced duct leakage) appear in the square root term. Balanced ventilation [for example energy recovery ventilators (ERV)] is additive.

$$\lambda_{tot,n} = \sqrt{\lambda_{inf,n}^2 + \lambda_{u,fan,n}^2 + \lambda_{u,l,n}^2} + \lambda_{b,fan,n} \tag{H.9}$$

where,

subscripts:

- $_b$ = balanced ventilation
- $_{inf}$ = infiltration
- $_{fan}$ = ventilation from a fan / mechanical ventilation
- $_l$ = leakage from ducts
- $_n$ = subscript of each hour of the year (n=1 to 8,760)
- $_{tot}$ = total air exchange rate, h^{-1}
- $_u$ = unbalanced mechanical ventilation

$\lambda_{tot,n}$ = total air exchange rate of house at hour n, h^{-1}
$\lambda_{inf,n}$ = natural infiltration rate at hour n, h^{-1}
$\lambda_{u,fan,n}$ = unbalanced mechanical ventilation rate at hour n, h^{-1}
$\lambda_{u,l,n}$ = unbalanced duct leakage rate at hour n, h^{-1}
$\lambda_{b,fan,n}$ = balanced mechanical ventilation rate at hour n, h^{-1}

For the ORNL test homes, all ducts are located within the conditioned space. As such, $\lambda_{u,l,n}$ is always 0 as any duct leakage is to the conditioned space. Thus, Eq. H.9 simplifies to Eq. H.10

$$\boldsymbol{\lambda_{tot,n} = \sqrt{\lambda_{inf,n}^2 + \lambda_{u,fan,n}^2} + \lambda_{b,fan,n}} \tag{H.10}$$

For scenarios that do not include an ERV, Eq. H.10 reduces to Eq. H.11, as there is no balanced mechanical ventilation.

$$\lambda_{tot,n} = \sqrt{\lambda_{inf,n}^2 + \lambda_{u,fan,n}^2} \tag{H.11}$$

For the ERV scenarios considered in this study there is no unbalanced ventilation term ($\lambda_{u,fan,n}$). As such, Eq. H.10 simplifies to Eq. H.12 since $\lambda_{inf,n}$ is the only unbalanced term inside the square root term.

$$\boldsymbol{\lambda_{tot,n} = \lambda_{inf,n} + \lambda_{b,fan,n}} \tag{H.12}$$

Hurel et al. (2015) compared twelve superposition models that have been proposed since the 1980s. They demonstrated that the additivity superposition model used in ASHRAE 62.2-2013 as shown in Eq. H.8 has root mean square (RMS) errors of ~20%. Further, the superposition model (quadrature as shown in Eq. H.11) described in the current ASHRAE Handbook of Fundamentals (ASHRAE, 2013f), which is used in EnergyPlus™ and also in the FREE model, has RMS errors of ~11%. The error in both the additivity and quadrature superposition models is a function of infiltration fraction, α, shown in Eq. H.13.

$$\boldsymbol{\alpha = \frac{\lambda_{inf}}{\lambda_{tot}}} \tag{H.13}$$

where,

α = infiltration fraction, unitless

In this study, additivity (Eq. H.8) is only used to determine the minimum ASHRAE 62.2-2013 required ventilation rate – providing a base case of required mechanical ventilation. Additivity underpredicts fan size by up to 30%, depending on α, Hurel et al. (2015). As this is the current required minimum ASHRAE 62.2-2013 ventilation rate, it provides a base case with minimum energy use for ventilation. If more accurate superposition models, such as those proposed by Hurel et al. (2015), are adopted in future editions of ASHRAE 62.2, without additional adjustments, the minimum required ventilation base case will require more energy than those reported in this study.

Both EnergyPlus™ v.7.2.0.006 and the FREE model use the quadrature superposition equations (Eq. H.9 – Eq. H.11) to determine the total ventilation rate and thus energy use. Hurel et al. (2015) show that the error of superposition using quadrature (over or under estimate the total ventilation rate by ~+5 to ~-11% depending on α) is much less than that for the additivity model (30%) described above. The impact of a more accurate superposition equation on additional energy used for ventilation above the minimum ASHRAE 62.2 required mechanical ventilation rate will be assessed, in the FREE model only, for constant mechanical ventilation rate in one test house at one location. The linear expression proposed by (Hurel et al., 2015) shown in Eq. H.14 in terms of air exchange rate is used for this comparison.

$$\boldsymbol{\lambda}_{\mathbf{tot}} = \boldsymbol{\lambda}_{\mathbf{fan}} + \frac{{\lambda_{\mathbf{inf}}}^{2}}{\lambda_{\mathbf{fan}}+\lambda_{\mathbf{inf}}} \tag{H.14}$$

where,

subscripts:

fan = ventilation from a fan / mechanical ventilation
inf = infiltration
tot = total ventilation

λ = air exchange rate, h^{-1}

H.1.3 Energy Calculation Procedures

Hourly outdoor temperature ($T_{o,n}$) and relative humidity ($\%RH_{o,n}$) are defined by the TMY3 weather data for each location. Hourly indoor temperature and %RH ($T_{i,n}$ and $\%RH_{i,n}$) are calculated using EnergyPlus™ models of a home, indoor set points, and ASHRAE minimum mechanical ventilation in Run 1 of EnergyPlus™ described in Section 6.1. The infiltration rate ($\lambda_{inf,n}$) and energy use for the home with no mechanical ventilation is found in Run 2 of EnergyPlus™ using the $T_{i,n}$ and $\%RH_{i,n}$ found in Run 1 as fixed inputs to EnergyPlus™ as described in Section 6.1. The same $T_{i,n}$ and $\%RH_{i,n}$ found in Run 1 of EnergyPlus™ are used with $T_{o,n}$ and $\%RH_{o,n}$ from the TMY3 weather data to calculate sensible, latent, and total enthalpy of the indoor and outdoor air for every hour of the year in the FREE model for every mechanical ventilation rate and GPF scenario (including the base case of ASHRAE minimum mechanical ventilation) as described below.

H.1.3.1 Model Assumptions

The following assumptions are used in the FREE model:

- The infiltration rates ($\lambda_{inf,n}$) calculated in Run 2 of the EnergyPlus™ model with no mechanical ventilation are constant for all GPF and mechanical ventilation scenarios.
- The correlations for C_{HCHO} shown in Eq. 6.1 and Eq. 6.2 are only valid for the HCHO emission rates of these specific houses, supply ventilation and are assumed to be valid for balanced ventilation. They are not valid for exhaust ventilation, but no exhaust ventilation scenarios are considered in this study.
- This study does not explore the effects of intermittent ventilation (e.g. bathroom or kitchen exhaust ventilation).
- The homes are unoccupied. While the EnergyPlus™ model does simulate occupancy from an energy perspective (heating water, opening the refrigerator, bathing, turning ON/OFF lights), it does not simulate the impact of occupant activities on C_{HCHO} (e.g., cooking, burning candles, smoking, use of personal care products, human exhalation of HCHO, etc.). Occupant activities on C_{HCHO} are not considered in this study.

- Air and water vapor each act as an ideal gas. This assumption is accurate to better than 99% from -40 to +50 ^{o}C and at or near atmospheric pressure – i.e., all the conditions we are concerned with (Gatley, 2005).
- The coefficient of performance (COP) of heating or cooling is constant for any hour of heating or cooling.
- The house is at steady-state at all times. This assumption is justified as:
    - Monthly and annual energy use is the end product so that small fluctuations are averaged out.
    - While small changes in AER and temperature can occur, these are minimized by the exceptional air tightness and insulation of the houses used in this study.
    - Indoor temperature and humidity set points are fixed for the heating and cooling season and are not adjusted during the day.
    - Mechanical ventilation rates are constant for all scenarios except those which use varying ventilation rates to achieve specified RELs for HCHO. In those cases, the formaldehyde concentrations vary only due to indoor temperature (which is fixed) and λ_{tot} (which varies slightly due to minor changes in infiltration rates throughout the day due to outdoor weather changes).

Standard pressure based on elevation is used as shown in Table H.1.

Table H.1 Standard Atmospheric Data – Corrected for Altitude

						Vol (m^3)	1278	Vol (m^3)	805
		a	b			WC2		WC3	
Location	**Elevation, Z (m)**	**Pressure, p (Pa)**	**Temperature, t (°C)**	**Std. Specific Volume of Dry Air corrected for altitude, v (m^3/kg)**	**Std. Air Density of dry air corrected for altitude, ρ (kg/m^3)**	**λ_{mAER} (h^{-1})**	**Mass Flow Rate of OA from mAER, m_{mAER}, kg/h**	**λ_{mAER} (h^{-1})**	**Mass Flow Rate of OA from mAER, m_{mAER}, kg/h**
Sea Level	0	101,325	20.0	0.8305	1.204				
Amarillo	1068	89,291	20.0	0.9424	1.061	0.145	197	0.084	72
Arcata	62	100,592	20.0	0.8365	1.195	0.154	235	0.112	108
Austin	213	98,826	20.0	0.8515	1.174	0.166	249	0.149	141
Buffalo	215	98,803	20.0	0.8517	1.174	0.147	221	0.090	85
Fairbanks	133	99,759	20.0	0.8435	1.186	0.144	218	0.084	80
Houghton	327	97,509	20.0	0.8630	1.159	0.146	216	0.085	79
Los Angeles	30	100,970	20.0	0.8334	1.200	0.165	253	0.147	142
Knoxville	293	97,900	20.0	0.8595	1.163	0.164	243.8	0.144	135

a. Adapted from Eqn 3 in ASHRAE Fundamentals 2013, Ch 1 $p=101325(1-2.225577\times10^{-5}Z)^{5.2559}$

b. EnergyPlus uses 20 °C as standard temperature

- A HCHO monitor/controller that is economically viable (i.e., can be paid for through energy savings) is or will be available with a minimum detection limit less than the REL being considered. The device would be installed in residences for controlling ventilation and gas-phase filtration equipment.
- A constant, outdoor concentration of formaldehyde $C_{HCHO,o}$ was assumed with average city-specific measurements used where available (i.e., 2 ppb in Oak Ridge and up to 15 ppb in Los Angeles). The 2 ppb is based on an average of 9 outdoor measurements taken in Oak Ridge (average 1.9, Std. Dev. ± 1.1, range 0.8-4 ppb). Where no city-specific data are available, 5.1 ppb was assumed based on the RIOPA study as reported by Salthammer (2013). A concentration of 1 ppb was assumed for rural areas (Houghton, MI, Arcata, CA and Fairbanks, AK). Outdoor formaldehyde concentrations ($C_{HCHO,o}$) used in modeling are summarized in Table H.2. As all

mechanically ventilated air was filtered through a HEPA/carbon filter, the impact of $C_{HCHO,o}$ on indoor C_{HCHO} is reduced.

Table H.2 Summary of $C_{HCHO,o}$ by City

City	$C_{HCHO,o}$ ppb
Amarillo	5
Arcata	1
Austin	5
Buffalo	5
Fairbanks	1
Houghton	1
Los Angeles	5 to 15
Knoxville	2

Indoor and outdoor carbon dioxide concentrations, $C_{CO2,OA}$ and $C_{CO2,IA}$ are needed for the one house/climate zone modeling scenario based on energy use of achieving a given $C_{CO2,IA}$.

- A constant outdoor concentration of carbon dioxide, $C_{CO2,\ OA}$, of 400 ppm was assumed at all locations.
- The CO_2 emission rate (E_{CO2}) used by Satish et al. (2012) of 0.0052 L/s per person is constant for all 4 individuals in the home.
    - o For CO_2 based ventilation calculations, 4 people are assumed to be present in the home 24 hours a day.
- The single-pass formaldehyde removal efficiency of all carbon filters remains constant at η_{GPF} = 0.60. This efficiency is based on two

measurements, a 1 hour sample in WC-2 before and after the carbon filter, which showed an 85% efficiency (reduction from 10. 2 to 1.2 ppb) taken by the author and a second 8-hour average efficiency of 60% (reduction from 24.5 to 9.8 ppb) measured by an independent laboratory (Matrix). The 60% efficiency was selected to be conservative. Measuring the variation of GPF efficiency over time was beyond the scope of this project.

- Energy use per volumetric flow rate is a function of fan type (ventilation fan, ERV and GPF) and is assumed to be the same in terms of $W/M^3/s$ regardless of the size of the flow. It is understood that this assumption is not true for all motor types. It is more valid for permanent split capacitor (PSC) motors than for electrically commutated (ECM) motors which are more efficient at lower flow-rates.
- ERV fan blade efficiency, η_F, is assumed to be 0.7 and constant.
- ERV motor efficiency, η_M, is assumed to be 0.9 and constant
- The fan blade and motor efficiencies were assumed based on information in the EnergyPlus™ Engineering reference manual and engineering estimates. For more refined estimates, once equipment requirements are defined, manufacture specification sheets can provide fan curve and motor efficiency curve data. Additional references that can be useful include Walker (2006) and Walker (2007).
- Monthly average soil temperatures (ranging from 17.8 to 24.8 ^oC) used in Oak Ridge, TN are used for all geographic locations. These impact the total

energy used to condition the house but do not impact the energy differential used for only mechanically ventilated air which is the key result of this study.

- The ground temperature will have some impact on the total energy use in WC-2 as it has a basement. This is mitigated by the insulation used in the basement and the fact that soil temperatures beneath conditioned basements are within a few ^{o}C of the indoor temperature (EnergyPlus™, 2012).

o The ground temperature will have a minimum impact on the total energy use in WC-3 as there is a ventilated crawlspace which is at approximately outdoor temperature.

The objective of the work reported by Hun et al. (2013a,b) was to report C_{HCHO} and energy use when defined ventilation flowrates were used as specified in ASHRAE Std. 62.2-2010. In contrast, the objective of this study is to determine optimal combinations of source reduction, T_{in}, and λ_{fan} to never exceed, on an hourly basis, the RELs of interest. To accomplish this objective, the correlations between C_{HCHO}, λ_{tot}, and T_{in} and the basic EnergyPlus™ model reported by Hun et al. (2013a) were applied. In addition, different base-case conditions were used to incorporate changes in minimum ventilation rates between the ASHRAE 62.2-2010 used by Hun et al. (2013a) and ASHRAE 62.2-2013 used in this study as well as relative humidity conditions recommended by U.S. EPA (2013a) for controlling moisture in buildings. To further generalize the results relative to the work of Hun et al (2013a), TMY3 weather data from the Knoxville airport were used. In Hun et al (2013a), site- and year-specific weather data were used to calibrate the λ_{inf} calculations in the EnergyPlus™ model for each house. The same calibrated EnergyPlus models for each house were used in this study. Additional details on how the calibration was done are presented in Section 6.4.1.

H.1.3.2 Limitations

- The data used in deriving the correlations for C_{HCHO} (Eq. 6.1 and Eq. 6.2) shown in Table H.3 do not cover the full range of indoor conditions explored by modeling. Uncertainty increases when these correlations are used outside the range of conditions for which they were derived. This may be particularly true for the lower (7 and 16 ppb) concentrations of C_{HCHO} in modeling. While these equations were used to extrapolate to higher total air leakage rates, it is noted that at ventilation rates above 0.5-0.6 h^{-1} and T_i < ~20 ^oC, the concentration of formaldehyde becomes negative. When this occured, $C_{HCHO,i}$ was set to $C_{HCHO,o}$ as in Tables 5.1 and 5.2.

Table H.3: Range of measured data used in correlation for C_{HCHO}

Parameter	WC-2	WC-3
Air Exchange Rates, λ_{tot}	0.012 -0.405 h^{-1}	0.109 -0.481 h^{-1}
Formaldehyde Concentration, C_{HCHO}	13 - 53 ppb	28 - 96 ppb
Indoor Temperature, T_i	22.8 - 27.5 ^oC	21.7 - 23.6 ^oC
Indoor Relative Humidity, $\%RH_i$	31 - 65%	42 - 61%

H.1.3.3 Unit Conversions

The following unit conversions were used:

- 100 cfm = 2.832 m^3/minute = 0.0472 m^3/s = 47.2 L/s
- 1 kJ/s = 1 kW ➔ 3600 kJ = 1 kWh
- 1 mm of water = 9.80665 Pa

H.1.3.4 FREE Model Equations

The following inputs are needed for the FREE model as previously shown in Chapter 6 in Figure 6.3:

- $T_{i,n}$,$\%RH_{i.n}$, $\lambda_{inf,n}$ = fixed inputs to FREE from EnergyPlus™ model for each location.

- $T_{o,n}$ and $\%RH_{o,n}$ = fixed inputs to FREE from TMY3 database for each location
- Mechanical ventilation rate for each hour of the year, $\lambda_{u,fan,n}$, h^{-1}
  - For ERV scenarios:
    - Balanced mechanical ventilation rate for each hour of the year, $\lambda_{b,fan,n}$, h^{-1}
    - Unbalanced mechanical ventilation rate for each hour of the year – in this case equal to the infiltration rate, $\lambda_{u,fan,n} = \lambda_{inf,n}$ as describe above using the work of (Mumma, 2010)
    - The sensible and latent heat efficiency of the ERV for each hour of the year, $\eta_{ERV,\ S,\ n}$ and $\eta_{ERV,\ L,\ n}$
  - HCHO removal efficiency of all gas phase filtration, η_{GPF}
  - Outdoor C_{HCHO}, o, n

Approach:

- Use Eq. H.15 - Eq. H.22 to calculate the specific enthalpy of air, h_{tot} in kJ/kg_{DA}. This is the specific enthalpy of the mixture of dry air (DA) and water vapor.
- Use Eq. H.23 and Eq. H.24 to calculate the mass flow rate of dry air for each hour of the year, $\dot{m}_{DA,n}$

- Use Eq. H.25 – Eq. H.29 to calculate electrical energy (kWh), E_n required in kWh to condition the ventilation air, $Q_{DA,n}$ for each hour of the year.
- Use Eq. H.30 – Eq. H.38 to calculate the annual electrical energy required in kWh to condition all of the ventilation air used throughout the year.

The saturation vapor pressure, p_{WS}, in Pa is obtained from Eq. H.15 for temperatures between 173.15 K and 273.15 K and Eq. H.16 for temperatures between 273.15 K and 473.15 K (ASHRAE(2013b), Gatley (2005)).

$$p_{WS,n} = EXP[C_1/T_n + C_2+C_3*T_n+C_4*(T_n)^2+C_5*(T_n)^3+C_6*(T_n)^4+C_7*\ln(T_n)] \quad (H.15)$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

$C_1 = -5.6745359 \times 10^{+3}$
$C_2 = 6.3925247$
$C_3 = -9.6778430 \times 10^{-3}$
$C_4 = 6.2215701 \times 10^{-7}$
$C_5 = 2.0747825 \times 10^{-9}$
$C_6 = -9.4840240 \times 10^{-13}$
$C_7 = 4.1635019$
T_n = temperature for hour n, K (173.15 to 273.15 K)
$p_{WS,n}$ = water vapor saturation pressure for hour n, Pa
Ln = natural logarithm
EXP = exponent

$$p_{WS,n} = EXP[C_8/T_n + C_9+C_{10}*T_n+C_{11}*(T_n)^2+C_{12}*(T_n)^3+C_{13}*\ln(T_n)] \quad (H.16)$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

C_8 = $-5.8002206 \times 10^{+3}$
C_9 = 1.3914993
C_{10} = $-4.8640239 \times 10^{-2}$
C_{11} = 4.1764768×10^{-5}
C_{12} = $-1.4452093 \times 10^{-8}$
C_{13} = 6.5459673
T_n = temperature for hour n, K (273.15 to 473.15 K)
$p_{WS,n}$ = saturation vapor pressure of water for hour n, Pa
Ln = natural logarithm
EXP = exponential

The partial pressure of water vapor, p_W, at the dry-bulb temperature, T, is derived from the known fractional relative humidity, Φ, as shown in Eq. H.17 (ASHRAE, 2013c).

$$p_{w,n} = \Phi_n * p_{ws,n} \tag{H.17}$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

$P_{w,n}$ = partial pressure of water vapor, Pa
$p_{ws,n}$ = water vapor saturation pressure, Pa
(from Eq. 6.15 or Eq. 6.)
Φ_n = relative humidity, fractional

The air humidity ratio, W, in mass of water vapor ($_{WV}$) per mass of dry air ($_{DA}$), kg_{WV}/kg_{DA} , is found using Eq. H.18 (ASHRAE, 2013c).

$$W_n = 0.621945 * p_{W\cancel{V,n}} / (p_n - p_{W\cancel{V,n}}) \qquad (H.18)$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

$W_{,n}$ = air humidity ratio, kg_{WV}/kg_{da}
$p_{W\cancel{V,n}}$ = partial pressure of water vapor, Pa
p_n = barometric pressure, Pa (hourly TMY3 data is used for each site)

The saturation humidity ratio, $W_s(t,p)$, is the humidity ratio of moist air saturated with respect to water (or ice) at the same temperature and pressure and is obtained from Eq. H.19 (ASHRAE, 2013c).

$$W_{s,n} = 0.621945 * p_{ws,n} / (p_n - p_{ws,n}) \qquad ` \qquad (H.19)$$

`where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

$W_{s,n}$ = humidity ratio of saturated moist air for hour n, kg_w/kg_{da}

$p_{ws,n}$ = water vapor saturation pressure for hour n, Pa
(from Eq. 6.15 or Eq. 6.)
p_n = barometric pressure for hour n, Pa (hourly TMY3 data is used for each site.)

The sensible and latent heat are calculated as shown in Eq. H.20 and Eq. H.21, respectively, with total specific enthalpy of moist air, h_{tot}, kJ/kg_{da}, shown in Eq. H.22 (ASHRAE, 2013b; The Engineering Toolbox, 2015).

$$h_{DA,n} = \text{Sensible heat} = 1.006*t \tag{H.20}$$

$$Wh_{g,n} = \text{Latent heat} = W_n*(2501 + 1.86*t) \tag{H.21}$$

$$h_{tot,n} = \text{Sensible heat} + \text{Latent heat} = h_{DA,n} + Wh_{g,n} \tag{H.22}$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

$h_{DA,n}$ = specific enthalpy of dry air for hour n, kJ/kg_{da}
$h_{g,n}$ = specific enthalpy for saturated water vapor for hour n, kJ/kg_w
$h_{tot,n}$ = specific enthalpy of moist air for hour n, kJ/kg_{da}
W_n = humidity ratio (at same T and p as h_{DA} and h_g) for hour n, kg_w/kg_{da}
T_n = dry-bulb air temperature for hour n, ^oC

The specific volume of a moist air mixture (v), expressed in terms of mass of dry air, is obtained from Eq. H.23 (ASHRAE, 2013c).

$$v_n = 0.287042*(t_n+273.15)*(1+1.607858*W_n)/p_n \qquad \text{(H.23)}$$

where,

subscript:

$_n$ = hour of the year (n=1 to 8,760)

v_n = specific volume of moist air mixture for hour n, m^3/kg_{DA}
t_n = temperature for hour n, ^oC
W_n = humidity ratio (at same t and p as v) for hour n, kg_w/kg_{da}
p_n = barometric pressure for hour n, Pa (the barometric pressure provided for each hour of the year in TMY3 data is used for each site)

The mass flow rate of mechanically ventilated air in terms of dry air, $\dot{m}_{da}$ (kg_{da}/s) is calculated using Eq. H.24.

$$\dot{m}_{DA,L,x,n} = {Q_{DA,L,x,n}}/{\upsilon_{DA,L,x,n}} \qquad \text{(H.24)}$$

where,

subscripts:
$_{DA}$ = dry air
$_L$ = Location
$_i$ = indoor
$_o$ = outdoor
$_x$ = type of airflow
$_{bal}$ = balanced
$_{unbal}$ = unbalanced
$_{GPF}$ = Gas Phase Filtration

n = hour of the year (n=1 to 8,760)

$\dot{m}_{DA,L,x,n}$ = mass flow rate of dry air in hour n, kg_{da}/s
$Q_{DA,L,x.n}$ = flow rate of mechanically transferred air, m^3/s
$\upsilon_{DA,L,x,n}$ = the specific volume of dry air, m^3/kg_{da}

- When the mass flow rate of ventilation air (balanced or unbalanced) is being calculated, outdoor air conditions are used.
- When the mass flow rate of indoor air through the gas phase filter is being calculated, indoor air conditions are used.

The sensible, latent, and total heat required to change the enthalpy of the mechanically ventilated incoming air from conditions found outdoors to those found indoors for each hour, n, of the year are calculated as shown in Eqs. H.25-H.28 using the mass flow rate, based on outdoor air conditions, of ventilation air (balanced or unbalanced). For balanced air flow equipment (e.g. ERVs), the sensible and latent efficiency of heat transfer between incoming and outgoing streams, $\eta_{sen,htx,n}$ and $\eta_{lat,htx,n}$ respectively are used. For unbalanced mechanical ventilation (e.g., supply ventilation, no infiltration), where no latent or moisture transfer occurs, $\eta_{sen,htx,n} = \eta_{lat,htx,n} = 0$.

$$q_{sen,x,n} = (1-\eta_{sen,htx,n}) * \dot{m}_{DA,L,x,n} * (h_{DA,i,n}-h_{DA,o,n}) \qquad \text{(H.25)}$$

$$q_{lat,x,n} = (1-\eta_{lat,htx,n}) * \dot{m}_{DA,L,x,n} * (Wh_{g,i,n} - Wh_{g,o,n}) \quad \text{(H.26)}$$

$$q_{tot,x,n} = q_{sen,x,n} + q_{lat,x,n} \quad \text{(H.27)}$$

$$q_{TOT,all\ x,\ n} = q_{tot,bal} + q_{tot,\ unbal} \quad \text{(H.28)}$$

where,

subscripts:

- DA = dry air
- L = Location
  - i = indoor
  - o = outdoor
- sen = sensible heat
- lat = latent heat
- tot = total for each flow type (bal or unbal) separately
- TOT = TOTAL for both flow types (bal and unbal) combined
- x = type of airflow
  - bal = balanced
  - unbal = unbalanced
- htx = heat exchanger
  - ERV-A = Energy Recovery Ventilator A
  - ERV-B = Energy Recovery Ventilator B
- n = hour of the year (n=1 to 8,760)

$\dot{m}_{DA,l,x,n}$ = mass flow rate of dry air in hour n, kg_{da}/s

$h_{DA,i,n}$ = specific enthalpy of indoor air for hour n at given conditions of T, %RH & p_{BAR}, kJ/kg_{da}

$h_{i,n}$ = specific enthalpy of indoor air for hour n at given conditions of T, %RH & p_{BAR}, kJ/kg_{da}

$\eta_{sen,htx,n}$ = sensible efficiency of heat exchanger, fractional

$\eta_{lat,htx,n}$ = latent efficiency of heat exchanger, fractional

$q_{lat,x,n}$ = latent heat required in hour n, kW_{th}

$q_{sen,x,n}$ = sensible heat required in hour n, kW_{th}

$q_{tot,x,n}$ = heat required in hour n, kW_{th}

$q_{TOT,all\ x,n}$ = heat required in hour n, kW_{th}

Note: if $q_{TOT,all\ x,n} > 0$, cooling is required that hour
if $q_{TOT,all\ x,n} < 0$, heating is required that hour

The thermal energy used to condition all mechanically ventilated air for the entire year, $q_{ann,cond}$ is calculated as shown in Eq. H.29.

$$q_{ann,cond} = \sum_{n=1}^{8760} q_n \times t \tag{H.29}$$

where,

subscripts:

$_n$ = hour of the year (n=1 to 8,760)

$q_{ann,\ cond}$ = thermal energy required annuallyl to condition mechanically ventilated air, kWh_{th}

q_n = total heat transfer required each hour of the year, kW_{th}

t = time increment of 1 h

The measured annual average COP_{Htg} and COP, r_{Clg} of the heat pump systems are used for any heating or cooling load, respectively as shown in Table H.4. As shown in Appendix A, the COP_{Htg} average values are from 14-17 months of data and the COP_{Clg} average values are from 17-22 months of data in homes WC-2 and WC-3 respectively.

Table H.4: Actual Annual Heat Pump System Efficiencies

House	Actual Average COP_{Htg}	Actual Average COP_{Clg}
WC-2	4.1	5.0
WC-3	3.6	4.2

See Appendix A: Table A3

For computational expediency, an annual average COP for each house was calculated using Eq. H.30 and Eq. H.31 based on weighting COP_{Htg} and COP_{Clg} using cooling degree days and heating degree days for each of the eight cities studied. It is recognized that this approach is not as precise as applying the COP_{Htg} and COP_{Clg} to each hour of thermal load.

$$TDD18.3_{CC} = HDD18.3_{CC} + CDD18.3_{CC} \tag{H.30}$$

$$\begin{aligned} COP_{ann\ avg,WC-n,CC} = {} & \left({}^{HDD18.3_{CC}}/_{TDD18.3_{CC}}\right) \times COP_{Htg,WC-n} \\ & + \left({}^{CDD18.3_{CC}}/_{TDD18.3_{CC}}\right) \times COP_{Clg,WC-n} \end{aligned} \tag{H.31}$$

where,

subscripts:

ann avg,WC-n,CC = Annual average for house WC-n in City CC

n = House number (2 or 3)

cc = City (AM, AL, AU, BU, FA, HO, LA, KN)

COP = Coefficient of Performance, nondimensional

HDD18.3 = Heating degree days with 18.3 ^{o}C base temperature

CDD18.3 = Cooling degree days with 18.3 ^{o}C base temperature

TDD18.3 = Total degree days with 18.3 ^{o}C base temperature

To determine the electric energy required to provide the thermal energy determined in the EnergyPlus™ and FREE Models for additional ventilation air, Eq. H.30 is used with the heating and cooling degree days for each city shown in Table H.5.

Table H.5: Heating and Cooling Degree Day Data

City/County	TMY3 Data Station	Heating Degree Days HDD18.3	Cooling Degree Days CDD18.3	Total Degree Days TDD18.3
Amarillo, TX / Potter & Randall	723630	4102	1366	5468
Arcata, CA / Humboldt	725945	4829	3	4832
Austin, TX / Travis	722540	1671	2962	4633
Buffalo, NY / Erie	725280	6508	563	7071
Fairbanks, AK/ Fairbanks North Star	702610	13517	72	13589
Houghton, MI / Houghton	727440	8879	234	9113
Los Angeles, CA / Los Angeles	722950	1295	582	1877
Knoxville, TN / Anderson & Roane	723260	3594	1514	5108

It is acknowledged that this approach is only an estimate and that actual COPs in each location will be different due to different soil temperatures and overall heating and cooling load at each site and may require different sizing of the HVAC equipment. Actual ground source heat pump (GSHP) data are only available using the design used in the ORNL houses at the tests sites in Oak Ridge, TN (near Knoxville). Detailed GSHP analysis for other configurations, designs and soil conditions is beyond the scope of this project. Use of furnace designs in cold climates is also beyond the scope of this project. Further, the use of GSPHs provides lower generation of greenhouse gases and thus the impact on climate change is less with a GSPH than a combustion furnace.

The annual average COPs calculated for both houses in each city using Eq. H.30 are shown in Table H.6.

Table H.6: Annual Average COPs for House WC-2 and WC-3

City	WC-2	WC-3
Amarillo, TX (AM)	4.3	3.7
Arcata, CA (AR)	4.1	3.6
Austin, TX (AU)	4.7	4.0
Buffalo, NY (BU)	4.2	3.6
Fairbanks, AK (FA)	4.1	3.6
Houghton, MI (HO)	4.1	3.6
Los Angeles, CA (LA)	4.4	3.8
Knoxville, TN (KN)	4.4	3.8
Average	4.3	3.7
Σ	0.2	0.1

Using annual average COP's shown in H.6, Eq. H.22 is modified to provide annual electricy worked for each year as shown in Eq. H.32

$$E_{ann,cond} = {q_{ann,cond}}/{COP_{ann\ avg}} \tag{H.32}$$

where,

subscripts:
$_{ann}$ = annual
$_{cond}$ = conditioned

$q_{ann,\ cond}$ = thermal energy required annually to condition mechanically ventilated air, kWhth
$E_{ann,\ cond}$ = electrical energy required on an annual basis to condition mechanically ventilated air, kWh/yr

H.1.4 Formaldehyde Emission Rate

The whole house formaldehyde emission rates as an hourly average ($ER_{HCHO,n}$), monthly average ($ER_{HCHO,mth}$) and annual average ($ER_{HCHO,ann}$) are calculated as shown in Eq. H.33 to Eq. H.35. These emission rates are used only for comparison with those reported by others, e.g., Turner et al. (2013). In this analysis, no separate adsorption/desorption or chemical reaction of HCHO is considered due to lack of data. Only a whole house emission rate was calculated, which incorporates the phenomenon.

$$ER_{HCHO,n} = c * (C_{HCHO,i,n} - C_{HCHO,o,n}) * \lambda_{tot,n} * V_{H^*}/1000 \qquad (H.33)$$

$$\mathrm{ER_{HCHO,mth}} = \frac{1}{(1+(\mathrm{b}-\mathrm{a}))} \sum_{\mathrm{n=a}}^{\mathrm{n=b}} \mathrm{ER_{HCHO,n}} \qquad (H.34)$$

$$\mathrm{ER_{HCHO,ann}} = \frac{1}{8760} \sum_{\mathrm{n=1}}^{\mathrm{n=8,760}} \mathrm{ER_{HCHO,n}} \qquad (H.35)$$

where,

subscripts:

- $_{H^*}$ = house (WC-2 or WC-3)
- $_{L}$ = location
  - $_{i}$ = indoor
  - $_{o}$ = outdoor
- $_{T}$ = time period
  - $_{ann}$ = annual
  - $_{mth}$ = month
    - a = 1st hour of the month
    - b = last hour of the month
  - $_{n}$ = hour of the year (n=1 to 8,760)

ER	= average whole house emission rate of formaldehyde over the time period, mg/h
$C_{HCHO,L,n}$	= concentration of formaldehyde, ppb
$\lambda_{tot,\,n}$	= total air exchange rate of house, h^{-1}
V_{H^*}	= conditioned volume of the house, m^3
c	= conversion constant = 0.00123 mg/m^3/ ppb

H.1.5 Energy Recovery Ventilators

Use of an Energy Recovery Ventilator (ERV) can significantly reduce the energy required to temper outdoor air and thus reduce the energy cost of ventilation compared with supply [positive (+ve) pressurization] ventilation. The American

Heating and Refrigeration Institute (AHRI) provides single point sensible and latent efficiency for commercially available ERVs (AHRI, 2015). EnergyPlus™ also makes provision for calculating energy savings from an ERV, assuming a fixed efficiency throughout the year.

In this study~~,~~ different ventilation rates are required throughout the year to reduce C_{HCHO} to prescribed values. Industry sources were approached with a request for equations for efficiency curves covering the full range of environmental conditions and flowrates anticipated in this study. One manufacturer provided detailed ERV efficiency information and permission to use and publish that data for this dissertation as described below.

Huizing and Kadylak (2013, 2014, 2015) provided the effectiveness and pressure drop correlations for two counter-flow ERV cores using data the manufacturer acquired through independent testing of their material at the University of Lucerne. Permission was requested and granted to use and publish these correlations for this dissertation (Kadylak, 2015). Effectiveness correlations, modified from data provided by Huizing & Kadylak (2013, 2014, 2015) to use flow rate in units of Std. m^3/s of dry air (da) (21^oC, 101.325 kPa of dry air with a corresponding specific volume of 0.818 m^3/kg_{da}) are presented below.

The FREE model incorporates ERV efficiency for every hour of the year, at different flow rates for the given environmental conditions.

H.1.5.1 Counter Flow ERV, ERV-A

Sensible and latent effectiveness correlations for a 366 x 366 x 378 mm (HxWxL) residential counter flow ERV core (ERV-A), with flow rates from 0.041 to 0.082 Std. m^3/s_{da}, are shown in order of highest to lowest effectiveness in Eq. H.36 to Eq. H.39 and graphically in Figure H.1.

$$\mathrm{Eff}_{\mathrm{Sen,\ To>Ti,\ ERV\text{-}A}} = -0.112 * \mathrm{Ln}\ (\mathrm{Q}_{\mathrm{ERV\text{-}A}}) + 0.443 \qquad \text{(H.36)}$$

where,

subscripts:

Sen = sensible
To>Ti = outdoor temperature greater than indoor temperature
ERV-A = energy Recovery Ventilator A

$\mathrm{Eff}_{\mathrm{Sen,\ To>Ti,\ ERV\text{-}A}}$ = sensible effectiveness when outdoor temperature is greater than indoor temperature of ERV-A, fractional

$Q_{ERV\text{-}A}$ = balanced air flow rate of air through ERV-A, Std. m^3/s_{DA}

$$\mathrm{Eff}_{\mathrm{Sen,\ To\leq Ti,\ ERV\text{-}A}} = -0.136 * \mathrm{Ln}\ (\mathrm{Q}_{\mathrm{ERV\text{-}A}}) + 0.367 \qquad \text{(H.37)}$$

where,

subscripts:

$_{Sen}$	= sensible
$_{To \leq Ti}$	= outdoor temperature less than or equal to indoor temperature
$_{ERV\text{-}A}$	= Energy Recovery Ventilator A

$Eff_{Sen,\ To \leq Ti,\ ERV\text{-}A}$	= sensible effectiveness when outdoor temperature is less than or equal to indoor temperature of ERV-A, fractional
$Q_{ERV\text{-}A}$	= balanced air flow rate of air through ERV-A, Std. m^3/s_{DA}

$$Eff_{Lat,\ To<Ti,\ ERV\text{-}A} = -0.231 * Ln\ (Q_{ERV\text{-}A}) - 0.068 \qquad \text{(H.38)}$$

where,

subscripts:

$_{Lat}$	= latent
$_{To<Ti}$	= outdoor temperature less than indoor temperature
$_{ERV\text{-}A}$	= Energy Recovery Ventilator A

$Eff_{Lat,\ To<Ti,\ ERV\text{-}A}$	= latent effectiveness when outdoor temperature is less than indoor temperature of ERV-A, fractional
$Q_{ERV\text{-}A}$	= balanced air flow rate of air through ERV-A, Std. m^3/s_{DA}

$$Eff_{Lat,\ To \geq Ti,\ ERV\text{-}A} = -0.229 * Ln\ (Q_{ERV\text{-}A}) - 0.105 \qquad \text{(H.39)}$$

where,

subscripts:

$_{Lat}$ = latent

$_{To \geq Ti}$ = outdoor temperature greater than or equal to indoor temperature

$_{ERV\text{-}A}$ = Energy Recovery Ventilator A

$Eff_{Lat,\ To \geq Ti,\ ERV\text{-}A}$ = latent effectiveness when outdoor temperature is greater than or equal to indoor temperature of ERV-A, fractional

$Q_{ERV\text{-}A}$ = balanced air flow rate of air through ERV-A, Std. m^3/s_{DA}

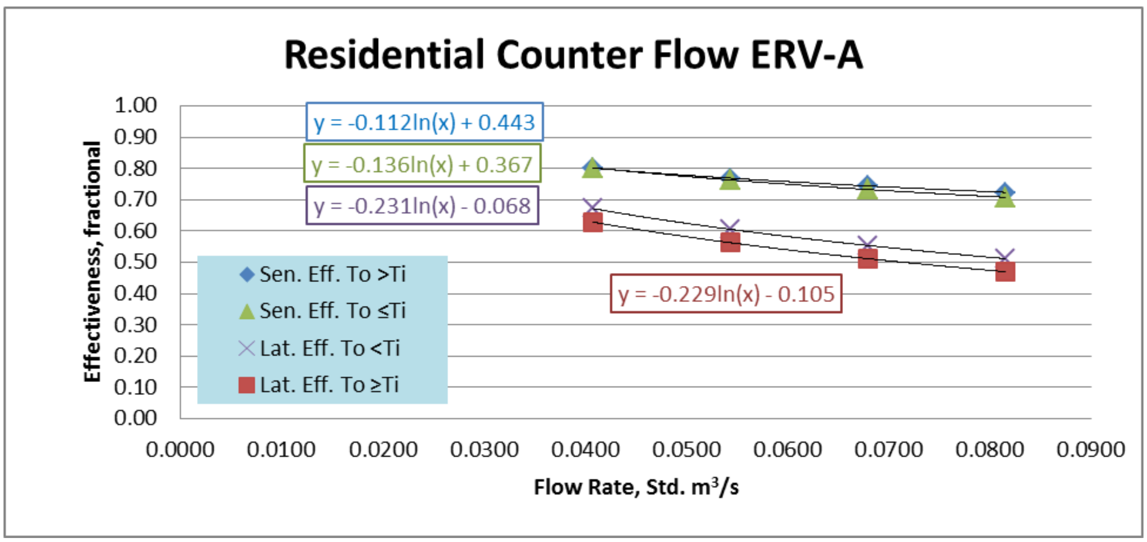

Figure H.1: Effectiveness Correlations for Residential ERV (ERV-A)

H.1.2 High Efficiency Counter Flow ERV, ERV-B

Effectiveness correlations for a larger 758 x 533 x 500 mm counter flow ERV core (ERV-B), with flow rates from 0.084 to 0.281 Std. m^3/s_{DA}, are shown in order of highest to lowest effectiveness in Eq. H.40, to Eq. H.43, and graphically in Figure H.2. Note that the order of effectiveness for ERV-B is different than for ERV-A. ERV-B is presented and used to show the impact of using a higher efficiency ERV. As higher ventilation rates are needed to achieve very low C_{HCHO} in these houses, multiple, or larger ERVs may be required.

$$Eff_{Sen,\ To>Ti,\ ERV\text{-}B} = -0.114 * Ln\ (Q_{ERV\text{-}A}) + 0.702 \qquad (H.40)$$

where,

subscripts:

Sen	= sensible
To>Ti	= outdoor temperature greater than indoor temperature
ERV-A	= energy Recovery Ventilator A

$Eff_{Sen,\ To>Ti,\ ERV\text{-}B}$	= sensible effectiveness when outdoor temperature is greater than indoor temperature of ERV-B,fractional
$Q_{ERV\text{-}B}$	= balanced air flow rate of air through ERV-B, Std. m^3/s_{DA}

$$Eff_{Lat,\ To\geq Ti,\ ERV\text{-}B} = -0.222 * Ln\ (Q_{ERV\text{-}A}) + 0.341 \qquad (H.41)$$

where,

subscripts:

Lat	= latent
To≥Ti	= outdoor temperature greater than or equal to indoor temperature

$_{ERV\text{-}B}$ = energy Recovery Ventilator B

$Eff_{Lat,\ To\geq Ti,\ ERV\text{-}B}$ = latent effectiveness when outdoor temperature is greater than indoor temperature of ERV-B, fractional

$Q_{ERV\text{-}B}$ = balanced air flow rate of air through ERV-B, Std. m^3/s_{da}

$$Eff_{Sen,\ To\leq Ti,\ ERV\text{-}B} = -0.112 * Ln\ (Q_{ERV\text{-}A}) + 0.524 \qquad (H.42)$$

where,

subscripts:

$_{Sen}$ = sensible
$_{To\leq Ti}$ = indoor temperature greater than or equal to outdoor temperature
$_{ERV\text{-}B}$ = energy Recovery Ventilator B

$Eff_{Sen,\ To\leq Ti,\ ERV\text{-}B}$ = sensible effectiveness when outdoor temperature is greater than indoor temperature of ERV-B, fractional

$Q_{ERV\text{-}B}$ = balanced air flow rate of air through ERV-B, Std. m^3/s_{da}

$$Eff_{Lat,\ To<Ti,\ ERV\text{-}B} = -0.229 * Ln\ (Q_{ERV\text{-}A}) + 0.062 \qquad (H.43)$$

where,

subscripts:

$_{Lat}$ = latent
$_{To<Ti}$ = outdoor temperature less than indoor temperature
$_{ERV\text{-}B}$ = Energy Recovery Ventilator B

$Eff_{Lat,\ Ti<To,\ ERV\text{-}B}$ = latent effectiveness when outdoor temperature is less than indoor

	temperature of ERV-B, fractional
$Q_{ERV\text{-}B}$	= balanced air flow rate of air through ERV-B, Std. m^3/s_{da}

For modeling the performance of an ERV, when more than the flow rate available from a single ERV is required, the maximum capacity of one ERV is used and then additional ERVs are added as needed.

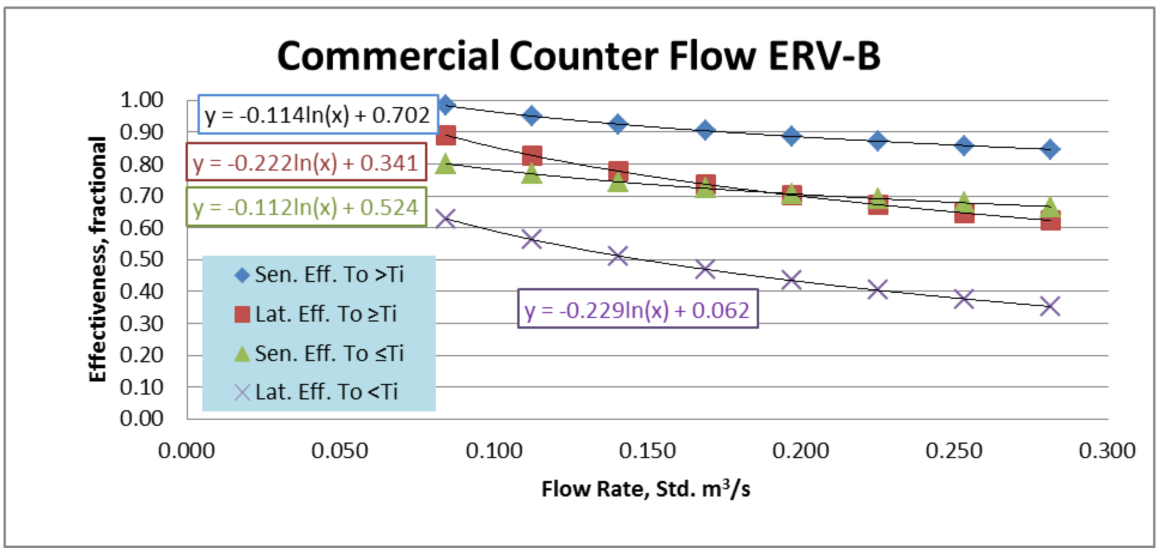

Figure H.2: Effectiveness Correlations for Commercial ERV (ERV-B)

H.1.6 Gas Phase Filtration

Use of gas phase filtration (GPF) may reduce the need for additional ventilation and thus save the energy required to condition additional outdoor air. GPF also uses some electrical energy to overcome the pressure drop of the gas phase filtration media and has significant media replacement cost after the media exceeds its' sorption capacity. FREE was used to explore the use of GPF and determine the allowable cost of GPF to reduce indoor concentrations of HCHO rather than doing so by additional ventilation.

Eq. 6.4 was modified to include the impact of GPF on the indoor concentration of HCHO as shown in Eq. H.44. The fact that GPF-C (see Figure 6.3) treats only indoor air is accounted for in the last term in Eq. H.44. This is done by proporotionally removing the impact of the concentration of formaldehyde in outdoor air ($C_{HCHO,o,n}$) that was used when the initial correlation (Eq. H.1) was derived. Eq. H.44 is analogous to Eq. H.4 and is used in the FREE model when calculating the indoor concentration for formaldehyde when both supply ventilation and GPF are used.

$$C_{HCHO,WC-2,i,n} = -90.4\left(\lambda_{tot} + \eta_{HCHO,GPF-C}\lambda_{GPF-C,n}\right) + 9.43T_i - 2747 + \left[C_{HCHO,o,n}(1-\eta_{GPF-A}) - 0.8\right] - 0.8\left[\frac{\eta_{HCHO,GPF-C}\lambda_{GPF-C,n}}{\left(\lambda_{tot} + \eta_{HCHO,GPF-C}\lambda_{GPF-C,n}\right)}\right] \tag{H.44}$$

where,

subscripts:

$_{HCHO,\ GPF-m}$ = formaldehyde gas phase filter-m where m = A, B, or C
L = location:
$_I$ = indoor

$_o$ = outdoor
$_n$ = hour of the year (n=1 to 8,760)
T = Type of air exchange rate
$_{mAER}$ = mechanical air exchange rate
$_{inf}$ = infiltration air exchange rate
$_{tot}$ = total air exchange rate (mAER and inf) – does not include GPF
$_{GPF-m}$ = gas phase filtration through filter-m where m =- A, B, or C
$_{WC-2}$ = house WC-2

λ = air exchange rate, h^{-1}
η = efficiency
$C_{HCHO,\ H^*,L,\ n}$ = formaldehyde concentration, ppb
T_i = temperature, K
$\eta_{HCHO,GPF-m}$ = HCHO removal efficiency for GPF, unitless

An equivalent total air exchange rate (i.e. the additional outdoor ventilation that would be needed to have the same reduction in C_{HCHO} as the GPF) can be defined that assumes an equivalence between outdoor ventilation and indoor GPF as shown in Eq. H.45.

$$\lambda_{tot-e} = \lambda_{tot} + \eta_{HCHO,\ GPF-C}\lambda_{GPF-C} \tag{H.45}$$

where,

λ_{tot-e} = equivalent total air exchange rate, h^{-1}

Eq. H.45 can be used to rewrite Eq. H.44 in terms of λ_{tot-e} as shown in Eq. H.46.

$$\begin{aligned} C_{HCHO,WC-2,i,n} = {} & -90.4\lambda_{tot-e} + 9.43T_i - 2747 \\ & + \left[C_{HCHO,o,n}(1-\eta_{GPF-A}) - 0.8\right] - 0.8\left[\frac{\eta_{HCHO,GPF-C}\lambda_{GPF-C,n}}{\lambda_{tot-e}}\right] \end{aligned} \tag{H.46}$$

Eq.H.45 can also be rewritten as shown in Eq. H.47 to calculate λ_{tot-e} when λ_{mAER} and λ_{inf} are known.

$$\lambda_{tot-e} = \sqrt{\lambda_{mAER}^2 + \lambda_{inf}^2} + \eta_{HCHO,\ GPF-C}\lambda_{GPF-C} \quad \text{(H.47)}$$

rearranging Eq. H.47,

$$\lambda_{GPF-C} = \frac{\lambda_{tot-e} - \sqrt{\lambda_{mAER}^2 + \lambda_{inf}^2}}{\eta_{HCHO,\ GPF-C}} \quad \text{(H.48)}$$

A clean air delivery rate (CADR) for the indoor GPF unit is defined as shown in Eq. H.49.

$$CADR = \eta_{HCHO,GPF-C} \times \lambda_{GPF-C} \times V \quad \text{(H.49)}$$

where,

CADR = clean are delivery rate, m^3/h
$\eta_{HCHO,GPF-C}$ = GPF efficiency, fractional
λ_{GPF-C} = GPF-C air exchange rate, h^{-1}
V = house volume, m^3

H.2 Model Parameters

H.2.1 Basis for Selection of Base Case Conditions

This section provides the rationale for selection of the base case conditions analyzed using EnergyPlus to determine annual energy use, hourly indoor temperature (T_{in}) and relative humidity ($\%RH_{in}$). The base case conditions are summarized in Table H.7. The mechanical ventilation rate, shown as an air exchange rate (λ_{fan}), is a site-specific parameter as described in section H.2.1.4.

Table H.7: Base Case Conditions for EnergyPlus™ models.

	WC-2	WC-3		
$T_{cooling}$	24.44 °C (76 °F)			
$T_{heating}$	21.67 °C (71 °F)			
$\%RH_{Dehum}$	48% if Tout ≥ 0 °C / 26% if Tout < 0 °C			
$\%RH_{Hum}$	20%			
$C_{HCHO, out}$	1 ppb (AR, FA, HO); 2 ppb (KNX); 5 ppb (AM, AU, BU); 5-15 ppb (LA)			
AER, λ_{tot}	0.197 h^{-1}	0.250 h^{-1}		
Site Specific Parameters:				
	City	**TMY3 Station**	WC-2	WC-3
Mechanical Ventilation, λ_{fan}	Amarillo (AM)	723630	0.145 h^{-1}	0.084 h^{-1}
	Arcata (AR)	725945	0.154 h^{-1}	0.112 h^{-1}
	Austin (AU)	722540	0.166 h^{-1}	0.149 h^{-1}
	Buffalo (BU)	725280	0.147 h^{-1}	0.090 h^{-1}
	Fairbanks (FA)	702610	0.144 h^{-1}	0.084 h^{-1}
	Houghton (HO)	727440	0.146 h^{-1}	0.085 h^{-1}
	Los Angeles (LA)	722950	0.165 h^{-1}	0.147 h^{-1}
	Knoxville (KN)	723260	0.164 h^{-1}	1.144 $^{-1}$

H.2.1.1 Modeling Locations

Modeling locations were selected to cover all eight Building America climate zones as shown in Figure H.3. A comparison Building America and other climate zones designated by ASHRAE and the Commercial Buildngs Energy Consumption Survey (CBECS) and detailed site information is shown in Table H.8.

Figure H.3: Modeling Sites – in Each of Eight Building America Climate Zones [8]

[8] Maps modified from (Baecheler et al. 2010) and (U.S. EIA, 2003)

Table H.8: Geographic Detail of Modeling

City/County	Building America Climate Zone[1]	IECC Climate Zone[2]	ASHRAE Climate Zone[3]	CBECS Climate Zone[4]	TMY3 Data Station[5]	Latitude[5]	Longitude[5]	Time Zone[5] (GMT)	Elevation[5] (m)
Amarillo, TX / Potter & Randall	Mixed-Dry	4	4B	4	723630	34.990	-101.9	-6	1068
Arcata, CA / Humbolt	Marine	4	4B	4	725945	40.983	-124.10	-8	62
Austin, TX / Travis	Hot-Humid	2	2A	5	722540	30.290	-97.74	-6	213
Buffalo, NY / Erie	Cold	5	4A	1	725280	42.933	-78.733	-5	215
Fairbanks, AK / Fairbanks North Star	Sub-artic	8	8	1	702610	64.817	-147.85	-9	133
Houghton, MI / Houghton	Very Cold	7	7	1	727440	47.167	-88.50	-5	327
Los Angeles, CA / Los Angeles	Hot-Dry	3	3B	4	722950	33.933	-118.40	-8	30
Knoxville, TN / Anderson & Roane	Mixed-Humid	4	4A	3	723260	35.820	-83.98	-5	293

[1] Building America Climate Regions – (Baecheler et al. 2010)
[2] IECC Climate Zones – (IECC, 2009)
[3] ASHRAE Climate Zones - (ASHRAE, 2010)
[4] CBECS Climate Zones - (U.S. EIA, 2003)
[5] Users' Manual for TMY3 Data Sets - (Wilcox & Marion, 2008)

H.2.1.2 Heating and Cooling Setpoints

The heating and cooling setpoints (21.67 ºC / 24.44 ºC) shown in Table H.7 are those used by Building America (Hendron and Engebrecht, 2010). These heating and cooling setpoints are used in EnergyPlus™ to determine the actual indoor temperature for each hour of the year ($T_{i,n}$) at ASHRAE 62.2-2016 minimum mechanical ventilation rates. EnergyPlus™ uses the hourly indoor temperature to calculate hourly infiltration rates which are subsequently used in the FREE model.

H.2.1.3 Dehumidification and Humidification Setpoints

The dehumidification set points are based on the latest guidance from the U.S. EPA (2013) which recommends the indoor dew point not exceed 12.78 ^oC (55 ^oF). At an indoor temperature of 24.44 ^oC (76 ^oF) a dew point of 12.78 ^oC is 48% RH as shown in Table 6.7. This is approximately the same value as the default value for indoor humidity in the intermediate method described in section 4.3.2.2 and 4.3.2.3 of ANSI/ASHRAE Standard 160-2009 (2009) of 50% (temperature not specified). When outdoor temperature falls below freezing, the dehumidification set point is set equal to U.S. EPA guidance (USEPA, 2013), which recommends a dew-point of 1.67 ^oC (35 ^oF) when the outdoor temperature falls below freezing. At an indoor temperature of 21.7 ºC (71 ºF) a dew-point of 1.67 ^oC is 26% RH as shown in Table 6.7. Note that when the outdoor temperature is less than 0 ºC when the indoor temperature is set to 21.7 ºC (71 ºF), depending on how well insulated the home is and if it is positively pressurized with respect to the outside, even lower RH may be needed to avoid condensation on windows or other cold surfaces (i.e., inside the walls). For this study, it is assumed that lower RH is not required due to the fact that the test homes are very well insulated and have low infiltration rates. For extremes in winter temperatures, it is recognized that this assumption may be incorrect.

The humidification set point is 20% RH based on the recommended minimum RH by Association of Surgical Technologies (2015) to prevent electrostatic discharge (ESD). To achieve this minimum RH in cold climates requires a humidifier.

The impact of correcting barometric pressure for the range of altitudes of the eight locations studied (0 to 1068 m) and the effect on calculating the humidification and dehumidification set points was analyzed and found to be of no significance. For this study, 48% RH is used as the dehumidification set point when $T_{out} > 0\ ^oC$ and 26% RH when $T_{out} < 0\ ^oC$. An RH of 20% was selected as the humidification set point. Measurement accuracy for RH in the experimental portion of this study was ±5% for indoor measurements, ±2% for outdoor measurements (from the on-site meteorological grade weather station).

H.2.1.4 Ventilation to ASHRAE 62.2-2016

Table H.9 shows the minimum total ventilation rates, Q_{tot}, required for house WC-2 and WC-3 by ANSI/ASHRAE Standard 62.2-2010 (ASHRAE, 2010a) and 62.2-2016 (ASHRAE, 2016)using the tabular method (Table 4.1b in both 62.2-2010 and 62.2-2016) and the corresponding minimum mechanical AERs (mAER).

Table H.9: ASHRAE 62.2-2016 Min.Required Total Ventilation Rates, Q_{tot}

	WC-2	WC-3
Floor Area, m^2	345	252
Number of Bedrooms, N_{br}	3	3
House Volume, m^3	1278	805
ASHRAE 62.2-2010		
Q_{tot}, L/s (from Table 4.1b)	35	28
Infiltration credit (10 L/s per 100 m^2)	35	25
Q_{tot} + Infiltration credit (L/s)	70	53
Minimum mAER, λ_{fan}, h^{-1}	0.10	0.13
ASHRAE 62.2-2016[a],		
Q_{tot}, L/s (from Table 4.1b)	70	56
Infiltration credit (0 L/s)	0	0
Q_{tot} + Infiltration Credit (L/s)	70	56
Minimum mAER, λ_{fan}, h^{-1}	0.20	0.25

[a] Without any infiltration credit

When the infiltration credit given in ASHRAE 62.2-2010 is added to the tabulated Q_{tot}, the total ventilation rate (within the accuracy of the tables) is the same. The minimum required mechanical ventilation rates, λ_{fan} required by ASHRAE 62.2-

2013 and -2016 are roughly twice those required by ASHRAE 62.2-2010. The ASHRAE 62.2-2010 required λ_{fan} were used by Hun et al. (2013a). The difference is due to the fact that ASHRAE 62.2-2010 provided a default infiltration credit and ASHRAE 62.2-2016 does not. ASHRAE 62.2-2016 provides a credit (reduction) in the amount of mechanical ventilation required, but only if infiltration has been estimated in the specific home using a blower door test.

Concurrent envelope leakage testing using a blower door was not available during the time formaldehyde samples and whole house air exchange rates measured using tracer gas were collected in the test houses. Blower door testing was collected 2 to 3 years previous to the IAQ field trial (Shrestha, 2013). The results of blower door tests shown in Table H.10 were done using the Canadian General Standards Board (CGSB) standard CGSB 149.10-M86 (CGSB, 1986) procedure with 8 point tests (from 50 to 15 Pa in 5 Pa intervals) and used Tectite version 2.19.7 software. Outputs from the blower door test shown in Table H.10 include: Air Exchange rate at 50 Pa (ACH50) in units of h^{-1}; CGSB equivalent leakage area at 10 Pa (L_{cgsb}) in units of m^2; and the exponent of building leakage curve (n).

Table H.10: Blower Door Tests on Test Houses WC-2 and WC-3

	WC-2[b]	WC-3[c]
Test Date	10/5/2009	7/8/2010
ACH50 (h^{-1})[a]	1.22	3.59
L_{cgsb} (m^2)[a]	0.047	0.102
n[a]	0.685	0.649

[a]Data provided by Shrestha (2013)

[b]Dryer and ERV vents were sealed.

[c]Air cycler vent was sealed. ACH50 is average of two tests on the same day.

While the validity of using the blower door testing taken in the same houses 2 to 3 years prior to this study in conjunction with the data collected in this study is unknown, it is used here simply to illustrate the ventilation credit given in ASHRAE 62.2-2013.

Table H.11 provides a summary of the calculations used in ASHRAE 62.2-2013 (ASHRAE, 2013a) to determine the required minimum mechanical ventilation rate. Details of the calculations can be found in (ASHRAE, 2016).

Table H.11: ASHRAE 62.2-2013 Ventilation Requirements for Test Houses

Parameter	**WC-2**	**WC-3**	**Parameter Description**[1]
A_{floor}, [m^2]	345	252	Floor Area
V, [m^3]	1280	805	House Volume
H, [m]	8.17	6.52	Vertical height above grade within the pressure boundary
N_{br}	3	3	Number of bedrooms
Q_{tot}, [L/s] Eqn	66	52	Total required ventilation rate, Eqn 4.1b[1]
Q_{tot}, [L/s]Table	**70**	**56**	Total required ventilation rate, Table 4.1b[1]
Test date	10/5/09	8/8/10	Blower door test date
ACH50, [h^{-1}]	1.22	3.59	Air Changes per hour measured at 50 Pa
L_{cgsb}, [m^2]	0.047	0.102	The CGSB 149.10 test leakage area
n, [n.d.]	0.682	0.649	Exponent of building leakage curve from CSGB 149.10 test
ELA, [m^2]	0.0243	0.0543	Effective Leakage Area, Eqn 4.3[1]
H_r [m]	2.5	2.5	Reference height
z, [n.d.]	0.4	0.4	Exponent of height correction
NL, [n.d.]	0.113	0.316	Normalized leakage Eqn 4.4[1]
Parameters below are location Specific for Knoxville (TMY3 723260):			
wsf, [n.d.]	0.430	0.430	Weather and shielding factors, Appendix B
Q_{inf}, [L/s]	11.6	23.8	Eff. Ann. Avg. Infiltration Rate, Eqn. 2.5b[1]
Q_{fan}, [L/s]	58	32	Required Mech. Ventilation Rate, Eqn. 4.6[1]
Summary of Values as λ in h^{-1} for Knoxville (TMY3 723260)			
λ_{tot}, [h^{-1}]	0.197	0.250	$\lambda_{tot} = Q_{tot}/V$
λ_{inf}, [h^{-1}]	0.033	0.106	$\lambda_{inf} = Q_{inf}/V$
λ_{fan}, [h^{-1}]	0.164	0.144	$\lambda_{fan} = Q_{fan}/V$

[1] Eqn., Table, Appendix and Addenda numbers refer to ASHRAE 62.2-2016

Test house WC-2 has a very low infiltration rate. Table 4 in Appendix G shows a spot λ_{tot} measurement by the author in WC-2 using the tracer gas decay method of 0.02 h^{-1}.

House WC-3 has a fairly tight home. Table 4 in Appendix G shows a spot AER measurement by the author in WC-3 using the tracer gas decay method of 0.10 h^{-1}.

For this study, the ASHRAE 62.2-2016 required minimum mechanical ventilation rate, λ_{fan}, calculated as shown in Table H.11 is used as the base case for each location. Note that λ_{fan} will be different for each geographic location due to different weather and shielding factors (wsf). Table H.12 provides a summary of the wsf and λ_{fan} for each of the eight locations studied.

The ASHRAE ventilation rate is a minimum rate and is not set to provide a specific quantifiable air quality metric. A history of ASHRAE ventilation rates is provided by (M. Sherman, 2015). Persily (2006) provides additional insight between the current disconnect between ventilation performance and design. Alternate ventilation rates, some of which are health based, are explored in the following section.

Table H.12: Base Case λ_{fan} for each of the 8 Geographic Locations

City, State/County	Building America Climate Zone	TMY Data Station	wsf[1]	λ_{fan} (h^{-1})	
				WC-2	WC-3
Amarillo, TX / Potter & Randall	Mixed Dry (MD)	723630	0.68	0.145	0.084
Arcata, CA / Humboldt	Marine (M)	725945	0.56	0.154	0.112
Austin, TX / Travis	Hot-Humid (HH)	722540	0.41	0.166	0.149
Buffalo, NY / Erie	Cold (C)	725280	0.65	0.147	0.090
Fairbanks, AK / Fairbanks North Star	Sub-Artic (SA)	702610	0.7	0.144	0.084
Houghton, MI / Houghton	Very Cold (VC)	727440	0.67	0.146	0.085
Los Angeles, CA / Los Angeles	Hot Dry (HD)	722950	0.42	0.165	0.147
Knoxville, TN / Anderson & Roane	Mixed-Humid (MH)	723260	0.43	0.164	0.144

[1]Site specific weather and shielding factor

H.2.2 Basis for Selection of Alternate Mechanical Ventilation Rates

In addition to ASHRAE 62.2-2013 minimum required ventilation rates, the energy impact and resultant C_{HCHO} are modeled for several alternative total air exchange rates, λ_{tot} [h^{-1}]. Scenarios studied are summarized in Chapter 6, Table 6.1 and 6.2.

H.2.2.1 CO2 based ventilation

As shown in Figure H.4, Satish et al. (2012) reported that elevated concentrations of CO_2 decrease decision-making performance: “Relative to 600 ppm, at 1,000 ppm CO_2, moderate and statistically significant decrements occurred in six of nine scales of decision-making performance. At 2,500 ppm, large and statistically significant reductions occurred in seven scales of decision-making performance (raw score ratios, 0.06–0.56), but performance on the focused activity scale increased” (From Satish et. al. (2012)).

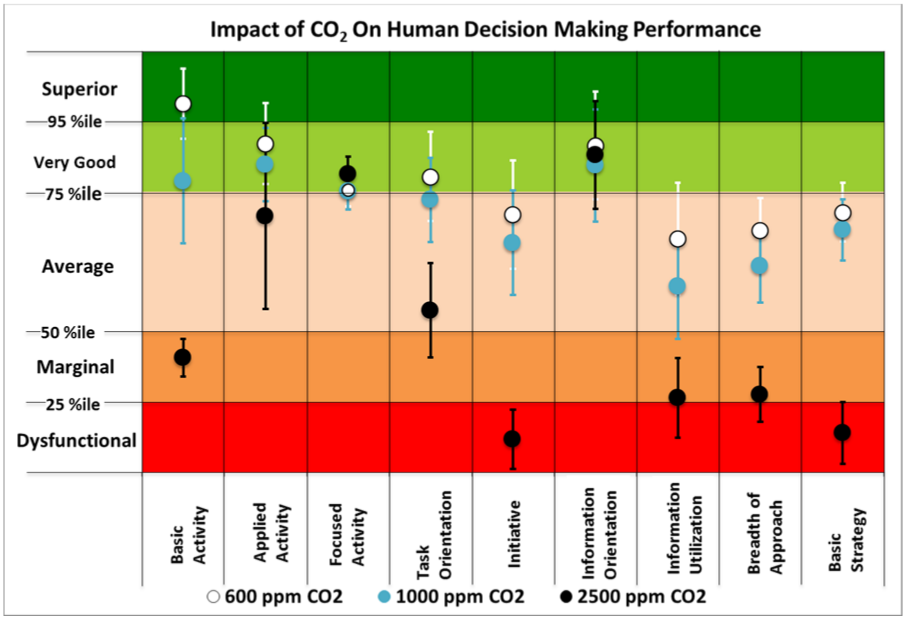

Figure from Satish et al. (2012)

Figure H.4: Impact of CO_2 on Human Decision Making Performance

Based on the Satish et al. (2012) study, keeping CO_2 concentrations near or below 600 ppm is ideal.

While it is recognized that outdoor CO_2 concentrations ($C_{CO2,OA}$) vary somewhat with location, time of day and time of year, a constant outdoor $C_{CO2,OA}$ of 400 ppm is assumed for this study at all locations. The latest annual average of monthly average CO_2 concentrations (Oct '14 – Sep '15) at the Mauna Loa Observatory is 400 ppm, and in the same period monthly averages range from 396-404 ppm (CO2 Now, 2015;NOAA 2015). While the emission rate of CO_2 by humans varies by time of day, age, weight, etc., for this study the CO_2 emission rate (E_{CO2}) used by

Satish et al. (2012) of 0.0052 L/person-s (34 g/person-h) is assumed to be constant for all 4 individuals in the home.

The required ventilation rate to achieve a desired steady-state C_{CO2} concentration assuming four people in each house is calculated as shown in Eq. H.50.

$$\lambda_{CO2,IA} = \frac{n \times E_{CO2}}{V \times (C_{CO2,IA} - C_{CO2,OA}) \times c_u} \tag{H.50}$$

where,

$\lambda_{CO2,\,IA}$ = air exchange rate to achieve the desired $CO_{2,\,IA}$, h^{-1}
c_u = units conversion factor = $\frac{\frac{1\,L}{10^6 L}}{ppm} \times \frac{44.01\frac{g}{mol}}{24.46\frac{L}{mol}} \times \frac{1000\,L}{1\,m^3} = 0.0018\ \frac{\frac{g}{m^3}}{ppm}$
n = number of people in the home, person
E_{CO2} = emission rate of CO_2, $\frac{g}{person*h}$
$CO_{2,IA}$ = steady-state concentration of CO_2 in indoor air, ppm
$CO_{2,OA}$ = steady-state concentration of CO_2 in outdoor air, ppm
V = Volume of house, m^3

Table H.13 shows the air exchange rates (AER) required in each of the test homes to achieve C_{CO2} of 600, 800 and 1,000 ppm with 4 people in the home, $C_{CO2,OA}$ = 400 ppm and E_{CO2} = 0.0052 L/person-s (34 g/person-h).

The houses studied are designed for low-density occupancy. To satisfy specific CO_2 concentrations only (i.e. not other CoC such as HCHO), additional outdoor air ventilation above baseline ventilation rates is only required if total ventilation rates (λ_{tot}) fall below those in Table H.13.

Table H.13: Required AER to achieve desired C_{CO2}

	WC-2	WC-3
$C_{CO2,IA}$ ppm	$\lambda_{CO2,\ IA}$, h^{-1}	$\lambda_{CO2,\ IA}$, h^{-1}
600	0.295	0.469
800	0.148	0.235
1000	0.098	0.156

H.2.2.2 Historical infiltration rate not requiring mechanical ventilation

Historically, ASHRAE Standard 62 required approximately 0.35 ACH for single-family homes (Sherman, 2004). Sherman considered this a “quite moderate ventilation requirement” and that “necessary mechanical ventilation may be closer to 1 ACH than to 0.35 ACH” in “high-occupant-density residential buildings”.

H.2.2.3 Health – Multidisciplinary review of the Scientific Literature

Sundell et. al (2011) report that homes with > 0.5 air changes per hour (ACH) were “associated with a reduced risk of allergic manifestations among children in a Nordic climate”.

H.2.2.4 Air Exchange Rates in U.S. Single Family Homes

Persily et al.(2010) modeled 209 homes throughout the U.S. and determined that the 90th percentile air exchange rate for single family homes was 1.0 ACH. This may be a reasonable upper bound of air exchange rates unless there are very high levels of contaminants in a home due to recent remodeling or other significant causes of elevated airborne contaminants.

Some European ventilation standards as described by Kunkel et al. (2015) are much higher than ASHRAE 62.2-2013 requirements. For example, Belgian Standard NBN D 50-001 "ventilation devices in residential buildings" requires 3.6 m^3/h per m^2 floor surface area (1 L/s m^2 or 0.197 cfm/ft^2). For WC-2, this is 810 cfm (1.08 h^{-1}) and for WC-3, 536 cfm (1.13 h^{-1}).

H.2.2.5 Ventilation Rates Based on Modeled VOC Emission Database

Ye et al. (2014) modeled VOC emissions from furnishings and building materials and showed that ventilation rates of greater than 1 ACH may be needed, particularly for the initial 3-5 months after remodeling and potentially for 2.5 to 5 years depending on what reference limits are selected.

Turner et al. (2013) evaluated the health benefits of reducing exposure to indoor contaminants and the energy cost of the ventilation. They found that “the health benefits dominated energy benefits independently of house size and climate”. They found that the net present value of energy cost and monetized Disability Adjusted Life Years (DALYs – a metric of the health impacts of exposure to indoor contaminants) justified ventilation rates of 30-100 cfm/person depending on the emission rate of formaldehyde, local energy costs, and climate.

In this study, constant mechanical ventilation rates for the entire year, based on the maximum emission rate, are calculated for 81, 40, 16, and 7 ppb for any REL less than that achieved with ASHRAE 62.2-2013 minimum ventilation rates.

H.2.2.6 Optimal (Varying) Ventilation Rates

One way to insure adequate ventilation to meet desired IAQ goals is to overventilate the space continuously. For example, one could ventilate at 2 ACH all the time as done in patient rooms in hospitals (AIA, 2014). However, these high levels of ventilation are likely not necessary to achieve desired concentrations of contaminants of concern in residences with the possible exception of extremely chemically sensitive individuals. Further, a high level of ventilation requires thermal conditioning of the ventilation air as well as removing or potentially adding moisture to provide a comfortable living environment. In addition, to insure that undesirable outdoor contaminants (dust, mold, pollen, ozone, fine particles, etc.) are not brought into the space, the incoming air may need to be filtered through a high efficiency filter and carbon (or other gas-phase) filters to remove particulate matter, ozone, HCHO, etc. The added monetary cost of treating the incoming air will, at some point, become more expensive than the health benefits provided by reducing contaminants of concern.

Ventilation rates are currently specified without regard to specific conditions in any given house or in the same house from day to day. To reduce the exposure to contaminants versus energy use, real-time sensors of contaminants of concern are needed that can adjust ventilation rates on demand, possibly with incorporation of real-time energy rates. This can currently be done with CO_2 demand controlled ventilation which is correlated with human occupancy and activities. However, CO_2 demand controlled ventilation does not account for changes in emission rates of formaldehyde or other contaminants of concern due to changes in indoor temperature and/or relative humidity, new furnishings, or use of personal care products.

It is proposed that a CO_2 monitor to measure human activity and a formaldehyde monitor to measure formaldehyde concentrations associated with building products and furnishings could provide optimal ventilation control when combined with energy and weather (T & RH) inputs. The ideal formaldehyde monitor would measure concentrations of concern, such as the CDC/FEMA/NIOSH 16 ppb requirement for manufactured housing, or potentially even the CA OEHHA 8-hour average concentration of 7 ppb.

In this study, variable mechanical ventilation rates are calculated that control hourly C_{HCHO} to the desired REL (81, 40, 16, 7 ppb). Note: this allows ventilation rates lower then the ASHRAE 62.2-2016 minimum total ventilation rate if the $C_{HCHO,i,n}$ is less than the desired REL. The modeled infiltration rate from EnergyPlus ($\lambda_{inf,\ EP}$) is used to calculate the hourly mechanical ventilation rate, λ_{fan} as shown in Eq. H.51.

$$\lambda_{fan} = \lambda_{tot} - \lambda_{inf,\ EP} \tag{H.51}$$

A high efficiency Energy Recovery Ventilator (ERV) can reduce the energy cost of conditioning the ventilation air, as well as provide balanced ventilation. The following section provides an example of energy savings potential from use of an ERV based on two high efficiency counter-flow ERV cores.

H.3 *Validation of Models*

H.3.1 Calibration of EnergyPlus™ Model

The EnergyPlus™ models for both WC-2 and WC-3 were calibrated for infiltration using measured air exchange rates (AERs) as briefly described by Hun et al., (2013a) (see Appendix A). This section provides additional details on how the calibration was performed.

The basic equation used by EnergyPlus™ to calculate infiltration for the entire house is based on the "flow coefficient" model by Walker and Wilson (1998), referred to in the ASHRAE Handbook of Fundamentals as the "Enhanced" or "AIM-2" model. The equation used by EnergyPlus is shown in Eq.H.52 (EnergyPlus™, 2012):

$$Inf = (F_{Schedule})\sqrt{(cC_s\Delta T^n)^2 + (cC_w(s * V_z)^{2n})^2} \tag{H.52}$$

For clarity, Eq. H.63 is rearranged as shown in Eqs. H.53 – H.55:

$$Inf = (F_{Schedule})\sqrt{c^2(C_s\Delta T^n)^2 + c^2(C_w(s * V_z)^{2n})^2} \tag{H.53}$$

$$Inf = (F_{Schedule})\sqrt{c^2[(C_s\Delta T^n)^2 + (C_w(s * V_z)^{2n}])^2} \tag{H.54}$$

$$Inf = c(F_{Schedule})\sqrt{(C_s \Delta T^n)^2 + (C_w (s * V_z)^{2n})^2} \quad \text{(H.55)}$$

where,

Inf = total infiltration/natural ventilation into the house, m^3/s
c = flow coefficient, $m^3/(sPa^n)$
$F_{Schedule}$ = 1 if schedule is ON / 0 if schedule is OFF
C_s = stack coefficient value, $(Pa/K)^n$ (0.089 for WC-2 and WC-3)*
ΔT = average difference between zone air temperature and outdoor air temperature, K
n = pressure exponent, dimensionless, typical value of n=0.67*, dimensionless
V_z = local wind speed (as given in weather data or at height of each zone depending on setting used in Energy+ - weather data was used in this work), m/s
C_w = Wind coefficient, $(Pas^2/m^2)^n$, (0.156 for WC-2; 0.142 for WC-3)*
s = shelter factor, dimensionless, from table (0.81 for WC-2 & 3 assuming shelter class 3)*

*Values selected for C_s, n, C_w, and s for WC-2 and WC-3 are from tabular values in ASHRAE (2005).

The "Enhanced" infiltration model described in ASHRAE (2005) uses a single "wind speed multiplier" of 0.59 for a two story house to account for the variation of wind speed with height above the ground. EnergyPlus™ calculates both the local wind speed, shown as V_z in Eq. H.67 and outdoor temperature for each zone and surface exposed to the outside. Either the zone or surface centroid (z axis) are used to determine the height above the ground (EnergyPlus™, 2012).

An on-site weather station at the test houses provided local hourly wind speed and temperature data for 2012 (coincident with the infiltration AER measurements). These weather data were used to extrapolate the local wind speed (wind speed at the z-axis centroid of each zone) as described in the EnergyPlus™ Engineering Reference document (EnergyPlus™, 2012) as shown in Eq. H.56.

$$V_z = V_{met} * \left(\frac{\delta_{met}}{z_{met}}\right)^{\propto_{met}} * \left(\frac{z}{\delta}\right)^{\propto} \quad \text{(H.56)}$$

where,

z = altitude, height above the ground, m
V_z = wind speed at altitude x, m/s
α = wind speed profile exponent at site, dimensionless
δ = wind speed profile boundary layer thickness at the site, m
z_{met} = height above the ground of the wind speed sensor at the meteorological station, m
V_{met} = wind speed measured at the meteorological station, m/s
α_{met} = wind speed profile exponent at the meteorological station, dimensionless
δ_{met} = wind speed profile boundary layer thickness at the meteorological Station, m

Values for the wind speed coefficients (α and δ) for houses WC-2 and WC-3 and coefficients (α_{met} and δ_{met}) for both the on-site and TMY3 weather stations are shown in Table H.14. All coefficients were obtained from tabulated values in the EnergyPlus™ Engineering Reference document (EnergyPlus™, 2012).

Table H.14: Wind Speed Profile Coeff. at ORNL and TMY3 Weather Stations

Parameter (units)	ORNL Weather Station	TMY3 Weather Station
α (dimensioless)	0.22	0.22
δ (m)	370	370
α_{met} (dimensionless)	0.22	0.14
δ_{met} (m)	370	270
z_{met} (m)	10.9	10

The infiltration model was calibrated by using 11 (WC-2) or 12 (WC-3) measured air exchange rates (AER) for infiltration only with no mechanical ventilation using the tracer gas approach described by Hun et al. (2013a). Actual 2012 weather data, including outdoor temperature and wind speed, from the on-site weather station at the test houses were used to calibrate the model. In the ORNL work, the flow coefficient "c" for the entire house that provided the best fit [0.0358 for WC-2 and 0.1125 for WC-3] to the measured data was obtained using a least-squares fit approach of modeled infiltration. The best fit "c" coefficient was adjusted for each zone by multiplying by the fractional volume of each individual zone compared to the total volume of the house. In this study, the flow coefficient "c" for the entire house that provided the best fit [0.0358 for WC-2 and 0.1125 for WC-3] to the measured data was obtained using a least-squares fit approach of modeled infiltration. Measured versus modeled AER for infiltration only used to obtain the calibrated whole house "c" values for WC-2 and WC-3 are shown graphically in Figure 6.8 and Figure 6.9 respectively. It is acknowledged that other calibration techniques could have been used to fit for Cs and Cw had adequate data been available.

Confidence limits on measured total air exchange rates, λ_{tot}, as reported by Hun et al. (2013) were obtained using the method described in ASTM E 741-00 (Reapproved 2006), Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. It is acknowledged that this approach may provide lower estimates of uncertainly than reported by others.

There are significant differences (-49% to +88% for WC-2 and -40% to +22% for WC-3) differences in the best fit obtained using a minimization sum of the squares method between the modeled and measured λ_{tot}. However, the average difference is much more reasonable (15% for WC-2 and -2% for WC-3).

Using the best fit "c" value provides a method of calibrating the EnergyPlus™ model for infiltration in both WC-2 and WC-3 using real-time, site specific weather data. These same calibrated EnergyPlus™ models developed in the ORNL work done by the author and reported in Hun et al. (2013), are used in the current work. It is acknowledged that this calibration approach does not accommodate extremes in weather where the accuracy of the correlation would decrease.

Figures H.5 and H.6 show the overall good correlation between the measured and modled AER using calibrated “c” values for Houses WC-2 and WC-3 respectively. This is true for λ_{tot} for both infiltration only at low (0.017 – 0.15 h^{-1}) λ_{tot} and infiltration combined with supply mechanical ventilation at higher (greater than 0.10 h^{-1}) λ_{tot}. Exhaust ventilation was not considered in these correlations.

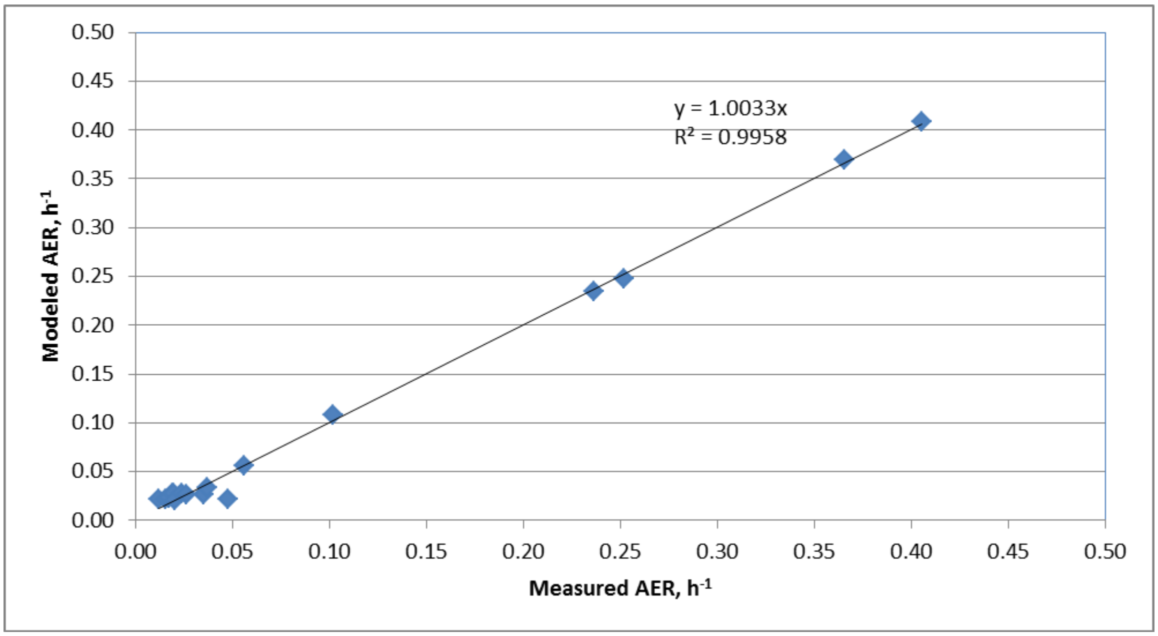

Figure H.5: WC-2 - Measured vs. Modeled λ_{tot} using calibrated “c”

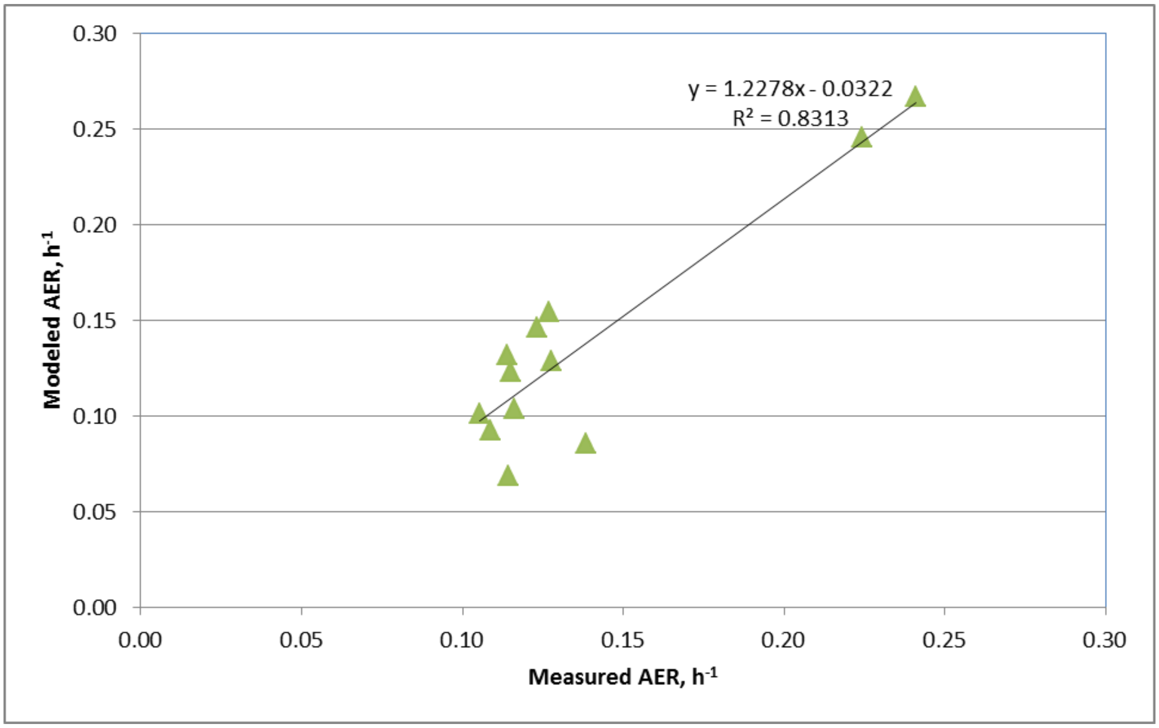

Figure H.6: WC-3 - Measured vs. Modeled λ_{tot} using calibrated "c"

H.3.2 Comparison of FREE and EnergyPlus™ Model

Table H.15 and Table H.16 provide comparisons of annual totals of energy used to condition test houses WC-2 and WC-3 using ASHRAE 62.2-2013 ventiation rates with both the EnergyPlus™ and FREE models. Energy used for the base case (ASHRAE 62.2-2013 mechanical ventilation + infiltration), obtained with the EnergyPlus™ model, is shown, as well as energy use with no mechanical ventilation or infiltration. For WC-2, an average of 33% of the annual energy use across all eight sites is used for ventilation as shown in Table H.15. For WC-3, an average of 50% of the annual energy use across all eight sites is used for ventilation as shown in Table H.16.

Table H.15: Comparison of EnergyPlus™ and FREE Model Results for WC-2

Location (Climate Zone)	Annual Energy Use (GJ/kWh_{th}/MBTU[1])										% Diff Between Models
	EnergyPlus™ Model							**FREE Model**			
	House + Ventilation			House Only			Fraction used for Ventilation	House + Venitilation			
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y		GJ/y	kWh_{th}/y	MBTU/y	
Amarillo, TX (Mixed-Dry)	75.6	21,000	71.7	52.7	14,639	50.0	0.30	75.2	20,889	71.3	**-0.5%**
Arcata, CA (Marine)	49.9	13,861	47.3	33.2	9,222	31.5	0.33	49.4	13,722	46.8	**-1.0%**
Austin, TX (Hot-Humid)	75.7	21,028	71.7	46.1	12,806	43.7	0.39	76.7	21,306	72.7	**1.3%**
Buffalo, NY (Cold)	97.7	27,139	92.6	63.1	17,528	59.8	0.35	94.6	26,278	89.7	**-3.2%**
Fairbanks, AK (Sub -Artic)	168.5	46,806	159.7	107.2	29,778	101.6	0.36	164.5	45,695	155.9	**-2.4%**
Houghton, MI (Very Cold)	122.9	34,139	116.5	78.2	21,722	74.1	0.36	118.9	33,028	112.7	**-3.3%**
Los Angeles, CA (Hot-Dry)	32.1	8,917	30.4	26.8	7,445	25.4	0.17	32.1	8,917	30.4	**0.0%**
Knoxville, TN (Mixed-Humid)	81.1	22,528	76.9	52.1	14,472	49.4	0.36	80.6	22,389	76.4	**-0.6%**
[1] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.							0.33	← Average over all sites →			-1.2%

Table H.16: Comparison of EnergyPlus™ and FREE Model Results for WC-3

Location (Climate Zone)	Annual Energy Use (GJ/kWh_{th}/MBTU[1])										% Diff Between Models
	EnergyPlus™ Model							**FREE Model**			
	House + Ventilation			House Only			Fraction used for Ventilation	House + Venitilation			
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y		GJ/y	kWh_{th}/y	MBTU/y	
Amarillo, TX (Mixed-Dry)	69.5	19,306	65.9	32.3	8,972	30.6	0.54	66.7	18,528	63.2	**-4.0%**
Arcata, CA (Marine)	38.1	10,583	36.1	16.4	4,556	15.5	0.57	33.9	9,417	32.1	**-11.0%**
Austin, TX (Hot-Humid)	60.4	16,778	57.2	34.4	9,556	32.6	0.43	62.3	17,306	59.0	**3.1%**
Buffalo, NY (Cold)	95.8	26,611	90.8	35.7	9,917	33.8	0.63	89.4	24,834	84.7	**-6.7%**
Fairbanks, AK (Sub -Artic)	180.9	50,250	171.5	60.5	16,806	57.3	0.67	171.3	47,584	162.4	**-5.3%**
Houghton, MI (Very Cold)	130.2	36,167	123.4	42.1	11,695	39.9	0.68	137.2	38,111	130.0	**5.4%**
Los Angeles, CA (Hot-Dry)	21.9	6,083	20.8	21.5	5,972	20.4	0.02	23.0	6,389	21.8	**5.0%**
Knoxville, TN (Mixed-Humid)	66.9	18,583	63.4	33.0	9,167	31.3	0.51	65.2	18,111	61.8	**-2.5%**
[1] MBTU as used in this dissertation represents a mega or 1,000,000 BTU.							0.50 ←	Average % Difference →			-2.0%

H.4 Fan Energy

Fan energy required to transport ventilation air through the ERV was ignored in the modeling analysis as it was assumed to be small relative to the energy required to transport ventilation air through the HEPA/carbon filter which was included in all scenarios.

A separate model analysis was perfomed using the approach developed in section H.4.1 below to determine the fan energy for the HEPA/carbon and GPF units. This analysis determined the relative amount of energy used by the ventilation fan in house WC-2 for both C mAER and DC mAER in all eight climate zones for the ASHRAE 62.2 base case and for C_{HCHO} <81, 40, 16 and 7 ppb. The relative amount of ventilation fan energy to total energy for the C mAER, 16 ppb GPF scenario in house WC-2 in Austin was also determined.

Section H.4.2 outlines the approach used to model the impact of inclusion of ERVC fan energy. The relative amount of ERVC fan energy to total enegy for the C mAER, 16 ppb ERV-A scenario in house WC-2 in Austin was determined.

H.4.1 Fan energy for HEPA/Carbon and GPF units

The minimum mechanical ventilation system efficacy, $\eta_{fan,\ IECC(2015)}$, required for in-line residential fans by the IECC (2015) is 2.8 cfm/watt [2.8 ft^3/(W-min) x 1 m^3 /

35.3147 ft^3 x 60 min /h x 1000 W/kW = 4800 m^3/kWh = 1.33 m^3/s/kW]. However, in this model, as ventilation air is through either a HEPA/GPF or a HEPA/GPF and an ERV, the energy required is higher.

Two carbon filter units (Amaircare model AWW675 filters with 13.6 kg canisters of carbon with a foam pre-filter) were measured with four replicates each using two 6" aluminum LoFlo Pitot traverse stations with digital differential pressure and flow transmitters. The average flowrate of all 8 measurements was 351 ± 12 cfm (0.166 ± 0.006 m^3/s). Simultaneous power consumption was 205 ± 5 W [2910 m3/kWh = 0.81 m^3/s/kW]].

Two measurements were made of the HEPA filter with an open cell foam pre-filter in the AWW675 units. The average flowrate was 398 cfm (0.188 m^3/s) with a simultaneous power consumption of 205 W [3300 m^3/kWh = 0.92 m^3/s/kW]. A 1.6 kg carbon canister was used inside the HEPA filter in the AWW675 units when ventilation air was introduced to the test houses. Lacking measurements of the flowrate, it is assumed that the flowrate and power consumption of the HEPA/1.6 kg of carbon is approximately the same as the 13.6 kg carbon canister [2910 m^3/kWh = 0.81 m^3/s/kW].

Using Eq. H.57, fan efficacy for the GPF units is 351 cfm/205 W = 1.71 cfm/W [2,910 m^3/kWh = 0.81 m^3/s/kW] with the 13.6 kg carbon canister and 1.94 cfm/W

[3,300 m^3/kWh = 0.92 m^3/s/kW] with the HEPA filter alone. The fan efficacy for the GPF with the HEPA filter and the 1.6 kg carbon filter, $\eta_{HEPA/Carbon}$, is assumed to be the same as the 13.6 kg carbon canister [2910 m^3/kWh = 0.81 m^3/s/kW].

$$\eta_{fan,\,x} = Q_{fan,x} / E_{fan,x} \tag{H.57}$$

where,

subscripts:

- $_x$ = type of airflow
- $_{bal}$ = balanced
- $_{unbal}$ = unbalanced
- $_{GPF}$ = Gas Phase Filtration
- $_{HEPA/GPF}$ = HEPA/GPF
- $_{fan}$ = all fan energy used for ventilation and filtered air

$\eta_{fan,\,x}$ = fan efficacy, m^3/s/kW
Q = flow rate of air through fan, m^3/s
E = electrial energy use of fan, kW

In this study, all mechanical ventilation (balanced or unbalanced) passes through a HEPA/carbon filter, thus $\eta_{fan,unbal} = \eta_{HEPA\text{-}Carbon}$. The energy required to filter all unbalanced $Q_{da,o,unbal,n}$, and balanced ventilation air, $Q_{da,o,bal,n}$, from the outside through the HEPA/carbon filters (GPF-A ad GPF-B) for each hour of the year is calculated as shown in Eq. H.58. Balanced ventilation has two fans as shown in the 2nd term in Eq. H.58. Recirculated air filtered through the indoor gas phase filtration (GPF-C) unit, which does not have a HEPA filter, is also calculated as shown in Eq. H.58. It is assumed that energy use per volumetric flow rate is a function of fan type (ventilation fan, ERV or GPF) and is the same in terms of W/M^3/s regardless of the size of the flow. For balanced airflow, it is assumed that there are two fans, thus the “2” in Eq. H.58.

$$E_{n,\ fan} = \frac{1}{\eta_{fan,HEPA/carbon}} * \left[Q_{DA,o,unbal,n} + Q_{DA,o,bal,n}\right] + 2 * \frac{1}{\eta_{fan,bal,n}} * Q_{DA,o,bal,n} + \frac{1}{\eta_{fan,GPF}} Q_{DA,i,GPF,n} \tag{H.58}$$

where,

subscripts:

- $_{DA}$ = dry air
- $_{L}$ = location
  - $_{i}$ = indoor
  - $_{o}$ = outdoor
- $_{x}$ = type of airflow
  - $_{bal}$ = balanced
  - $_{unbal}$ = unbalanced
  - $_{GPF}$ = gas phase filtration
- $_{HEPA/carbon}$ = HEPA/carbon filter
- $_{n}$ = hour of the year (n=1 to 8,760)
- $_{fan}$ = all fan energy used for ventilation and filtered air

$E_{n,\ fan}$ = energy used in each hour of the year to move mechanically transferred air, kWh

$Q_{DA,L,x,n}$ = flow rate of mechanically transferred air, m^3/s

$\eta_{fan,\ x}$ = fan efficacy, m^3/s/kW

The energy used annually, to move mechanically transferred air is summed as shown in Eq. H.59.

$$E_{ann,\ fan} = \sum_{n=1}^{n=8,760} E_{n,fan} \qquad \text{(H.59)}$$

where,

subscripts:

$_{n}$ = hour of the year (n=1 to 8,760)

$_{mth}$ = month (Jan – Dec)

$_{ann}$ = annual

$_{fan}$ = all fan energy used for ventilation and filtered air

$E_{mth,\ fan}$ = energy used in specific month to move mechanically transferred air, kWh/mth

$E_{ann,\ fan}$ = energy used in a year to move mechanically transferred air, kWh/year

a = first hour in the month

b = last hour in the month

The total energy used for conditioning and moving mechanically transferred air annually is calculated as shown in Eq. H.60.

$$E_{ann,tot} = E_{ann,cond} + E_{ann,fan} \qquad \text{(H.60)}$$

where,

subscripts:

$_{ann}$ = annual

$_{tot}$ = total

$_{cond}$ = conditioned

$_{fan}$ = all fan energy used for ventilation and filtered air

$E_{Ann,EU}$ = energy used for given task, kWh/yr

H.4.2 Fan Energy for ERVs

This analysis was only used to determine the relative energy use of the ERV fan compared to ventilation filtration through the HEPA/Carvbon filter and total energy for one scenario (WC-2 in Austin at C_{HCHO} = 16 ppb). Pressure drops across ERV-A and ERV-B are calculated as shown in Eq. H.61 and Eq. H.62 respectively which were provided by Huzing and Kadylak (2013, 2014, 2015) as described in section H.1.5.

$$dP_{ERV-A,n} = 4050 * \left(Q_{ERV-A,n}\right)^{1.44} \tag{H.61}$$

where,

subscripts:

$_{ERV\text{-}A}$ = Energy Recovery Ventilator A
$_{n}$ = hour of the year (n=1 to 8,760)

$dP_{ERV\text{-}A,n}$ = pressure drop across ERV-A in hour n, Pa
$Q_{ERV\text{-}A,n}$ = balanced air flow rate of air through ERV-A in h our n, m^3/s_{DA}

$$dP_{ERV-B,n} = 453 * \left(Q_{ERV-B,n}\right)^{1.23} \tag{H.62}$$

where,

subscripts:

$_{ERV\text{-}B}$ = Energy Recovery Ventilator B
$_{n}$ = hour of the year (n=1 to 8,760)

$dP_{ERV-B,n}$ = pressure drop across ERV-B in hour n, Pa
$Q_{ERV-B,n}$ = balanced air flow rate of air through ERV-B in hour n, m^3/s_{DA}

The power to provide airflow (P_A) and overcome static pressure for the ERV-A and ERV-B were calculated as shown in Eqn. H.63 (The Engineering Toolbox, 2017)

$$P_{A,n} = Q_{ERV-x,n} * dP_{ERV-x,n} \tag{H.63}$$

where,

subscripts:
$_A$ = air
$_{ERV-x}$ = ERV-A or ERV-B
$_n$ = hour of the year (n=1 to 8,760)

$P_{A,n}$ = air power in hour n, W
$Q_{ERV-x,n}$ = flow rate through ERV in hour n, m^3/s
$dP_{ERV-x,n}$ = pressure differential across ERV in hour n, Pa

The power required at the fan shaft (P_F) is determined by Eq. H.64.

$$P_{F,n} = P_{A,n} / \eta_{FB} \tag{H.64}$$

where,

subscripts:
$_A$ = air
$_F$ = fan
$_{FB}$ = fan blade

$_n$ = hour of the year (n=1 to 8,760)

$P_{fan,n}$ = fan power in hour n, W
P_A,n = air power in hour n, W
η_{FB} = fan blade efficiency, fractional

For this study, fan efficiency, η_{FB}, is assumed to be 70% and constant. The fan efficiency range of 50-70% is given in the ASHRAE Handbook of Fundamentals (ASHRAE, 2013e).

The power required at the input to the motor, assuming a direct connected shaft (i.e. no belt drive), is shown by Eq. H.65, which is adapted from ASHRAE (2013d).

$$P_{M,n} = P_{F,n} / \eta_M \tag{H.65}$$

where,

subscripts:
$_M$ = motor
$_F$ = fan
$_n$ = hour of the year (n=1 to 8,760)

$P_{M,n}$ = motor power in hour n, W
$P_{F,n}$ = fan power in hour n, W
η_M = motor efficiency, fractional

For this study, motor efficiency, η_M, is assumed to be 90% and constant based on a range of general motor efficiencies of 80 to 95% reported by ASHRAE (2013e).

By combining Eqs. H.51 to H.52, the energy used in each hour of the year to move air through the ERV is given by Eqn. H.66.

$$E_{fan,bal,n} = 2 * 96.144 * Q_{ERV-x,n} * dP_{ERV-x,n} \qquad \text{(H.66)}$$

where,

subscripts:

$_{ERV\text{-}x}$ = ERV-A or ERV-B
$_{fan}$ = fan
$_{n}$ = hour of the year (n=1 to 8,760)

Recognizing that the ERVs are balanced airflow, Eq. H.66 can be re-written to obtain the ERV fan efficacy, $\eta_{fan,\ x}$ in $m^3/s/kW$ as shown in Eq. H.67.

$$\eta_{fan,\ bal,n} = \eta_{fan,\ ERV\text{-}i,n} = Q_{fan,ERV\text{-}x} / E_{fan,ERV\text{-}i} \qquad \text{(H.67)}$$

where,

subscripts:

$_{bal}$ = balanced airflow
$_{ERV\text{-}i}$ = ERV-A or ERV-B
$_{fan}$ = fan
$_{n}$ = hour of the year (n=1 to 8,760)

$\eta_{fan,\ ERV\text{-}i}$ = ERV-i fan efficacy, $m^3/s/kW$

Appendix I: FREE Modeling Results

Abbreviations Used in Appendix I

Ann. Avg.	Annual Average
AU	Austin, TX
C/DC	Constant / Demand Controlled (mAER)
$C_{HCHO,i,n}$	Indoor Formaldehyde Concentration for any hour, n
$C_{HCHO,o}$	Outdoor Formaldehyde Concentration
DALYs	Disability Adjusted Life Years
ER	Emission Rate
LA	Los Angeles, CA
mAER	Mechanical Air Exchange Rate, h^{-1}
Min	Minimum
Non-Cap.	Non-Capital Cost (i.e. of any equipment, including installation)
SCC	Societal Cost of Carbon
w	with

Cell Legend:

(shaded cell)	mAER < ASHRAE 62.2-2016 minimum required ventilation rate
$$$	*M*inimum cost for DALY risk level
$$$	Savings

Table I.1: WC-2 Thermal Energy Summary: C/DC mAER, T_{Clg}=24.4 ºC

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	75.2	20,889	71.3	63.4	17,611	60.1	86.5	24,028	82.0	130.3	36,195	123.5	148.0	41,111	140.3
Arcata, CA (Marine)	49.4	13,722	46.8	38.4	10,667	36.4	54.4	15,111	51.6	93.6	26,000	88.7	109.7	30,472	104.0
Austin, TX (Hot-Humid)	76.7	21,306	72.7	52.6	14,611	49.9	88.8	24,667	84.2	145.8	40,500	138.2	168.3	46,750	159.5
Buffalo, NY (Cold)	94.6	26,278	89.7	80.7	22,417	76.5	107.7	29,917	102.1	160.9	44,695	152.5	182.4	50,667	172.9
Fairbanks, AK (Sub -Artic)	164.5	45,695	155.9	142.5	39,584	135.1	182.2	50,612	172.7	269.5	74,862	255.4	304.2	84,501	288.3
Houghton, MI (Very Cold)	118.9	33,028	112.7	101.4	28,167	96.1	131.7	36,584	124.8	196.4	54,556	186.2	222.4	61,778	210.8
Los Angeles, CA (Hot-Dry)	32.1	8,917	30.4	27.5	7,639	26.1	35.6	9,889	33.7	60.9	16,917	57.7	72.9	20,250	69.1
Knoxville, TN (Mixed-Humid)	80.6	22,389	76.4	60.9	16,917	57.7	89.1	24,750	84.5	140.7	39,084	133.4	161.5	44,861	153.1

Location (Climate Zone) TClg = 24.4 oC	Annual Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	75.2	20,889	71.3	63.4	17,611	60.1	70.1	19,472	66.4	96.2	26,722	91.2	112.7	31,306	106.8
Arcata, CA (Marine)	49.4	13,722	46.8	38.4	10,667	36.4	38.4	10,667	36.4	52.8	14,667	50.0	66.8	18,556	63.3
Austin, TX (Hot-Humid)	76.7	21,306	72.7	52.6	14,611	49.9	78.4	21,778	74.3	127.0	35,278	120.4	148.7	41,306	140.9
Buffalo, NY (Cold)	94.6	26,278	89.7	80.7	22,417	76.5	83.6	23,222	79.2	108.6	30,167	102.9	128.3	35,639	121.6
Fairbanks, AK (Sub -Artic)	164.5	45,695	155.9	142.5	39,584	135.1	142.2	39,500	134.8	172.4	47,889	163.4	203.4	56,500	192.8
Houghton, MI (Very Cold)	118.9	33,028	112.7	101.4	28,167	96.1	102.9	28,584	97.5	128.7	35,750	122.0	152.4	42,334	144.4
Los Angeles, CA (Hot-Dry)	32.1	8,917	30.4	27.5	7,639	26.1	28.9	8,028	27.4	40.2	11,167	38.1	50.7	14,083	48.1
Knoxville, TN (Mixed-Humid)	80.6	22,389	76.4	60.9	16,917	57.7	73	20,278	69.2	106.4	29,556	100.8	125.9	34,973	119.3

Location (Climate Zone) T_{Clg} = 24.4 °C	% Energy Savings from Demand Controlled vs. Constant mAER						
				$C_{HCHO,i,n}$ ≤ 81 ppb	**$C_{HCHO,i,n}$ ≤ 40 ppb**	**$C_{HCHO,i,n}$ ≤ 16 ppb**	**$C_{HCHO,i,n}$ ≤ 7 ppb**
					House + Venitilation	House + Venitilation	House + Venitilation
				%	%	%	%
Amarillo, TX (Mixed-Dry)				0%	19%	26%	24%
Arcata, CA (Marine)				0%	29%	44%	39%
Austin, TX (Hot-Humid)				0%	12%	13%	12%
Buffalo, NY (Cold)				0%	22%	33%	30%
Fairbanks, AK (Sub -Artic)				0%	22%	36%	33%
Houghton, MI (Very Cold)				0%	22%	34%	31%
Los Angeles, CA (Hot-Dry)				0%	19%	34%	30%
Knoxville, TN (Mixed-Humid)				0%	18%	24%	22%
Average All Zones				0%	20%	31%	28%

[a] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.

Cell Legend: (shaded cell) mAER < ASHRAE 62.2-2016 minimum required ventilation rate

Table I.2: WC-2 mAER and C_{HCHO} Summary: C/DC mAER, T_{Clg}=24.4 ^{o}C

Location (Climate Zone) T_{Clg} = 24.4 ^{o}C	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER CHCHO,i,n ≤ 81 ppb			Constant mAER CHCHO,i,n ≤ 40 ppb			Constant mAER CHCHO,i,n ≤ 16 ppb			Constant mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i\ ppb}$	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.145	47	29	0.000	60	37	0.226	40	22	0.492	16	6	0.591	7	3
Arcata, CA (Marine)	0.154	44	19	0.000	56	29	0.198	40	15	0.464	16	1	0.564	7	0
Austin, TX (Hot-Humid)	0.166	45	34	0.000	60	46	0.226	40	29	0.492	16	9	0.592	7	4
Buffalo, NY (Cold)	0.147	47	25	0.000	59	33	0.226	40	19	0.492	16	4	0.596	7	3
Fairbanks, AK (Sub -Artic)	0.144	46	20	0.000	58	28	0.209	40	15	0.474	16	2	0.574	7	1
Houghton, MI (Very Cold)	0.146	46	22	0.000	58	30	0.208	40	17	0.474	16	2	0.574	7	1
Los Angeles, CA (Hot-Dry)	0.165	45	29	0.000	59	40	0.226	40	23	0.492	16	5	0.591	7	3
Knoxville, TN (Mixed-Humid)	0.164	44	28	0.000	59	39	0.213	40	24	0.479	16	6	0.578	7	2

Location (Climate Zone) T_{Clg} = 24.4 ^{o}C	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER CHCHO,i,n ≤ 81 ppb			Demand Controlled mAER CHCHO,i,n ≤ 40 ppb			Demand Controlled mAER CHCHO,i,n ≤ 16 ppb			Demand Controlled mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.145	47	29	0.000	60	37	0.073	40	32	0.305	16	15	0.405	7	7
Arcata, CA (Marine)	0.154	44	19	0.000	56	29	0.002	40	29	0.197	16	16	0.296	7	7
Austin, TX (Hot-Humid)	0.166	45	34	0.000	60	46	0.122	40	29	0.370	16	9	0.470	7	4
Buffalo, NY (Cold)	0.147	47	25	0.000	59	33	0.045	40	30	0.262	16	15	0.363	7	7
Fairbanks, AK (Sub -Artic)	0.144	46	20	0.000	58	28	0.017	40	27	0.211	16	15	0.311	7	6
Houghton, MI (Very Cold)	0.146	46	22	0.000	58	30	0.026	40	28	0.225	16	15	0.327	7	6
Los Angeles, CA (Hot-Dry)	0.165	45	29	0.000	59	40	0.065	40	36	0.313	16	16	0.411	7	7
Knoxville, TN (Mixed-Humid)	0.164	44	28	0.000	59	39	0.076	40	33	0.302	16	16	0.402	7	7
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Table I.3: WC-2 Energy Cost w SCC: C/DC mAER, T_{Clg}=24.4 °C

Location (Climate Zone) TClg = 24.4 oC	Total Annual Energy Cost Including Societal Cost of Capital ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$778	$588	$927	$1,481	$1,700
Arcata, CA (Marine)	$705	$466	$796	$1,455	$1,719
Austin, TX (Hot-Humid)	$707	$425	$836	$1,436	$1,670
Buffalo, NY (Cold)	$1,335	$1,044	$1,564	$2,452	$2,809
Fairbanks, AK (Sub-Artic)	$2,594	$2,140	$2,915	$4,453	$5,060
Houghton, MI (Very Cold)	$1,431	$1,141	$1,615	$2,514	$2,870
Los Angeles, CA (Hot-Dry)	$477	$311	$558	$1,028	$1,231
Knoxville, TN (Mixed-Humid)	$744	$500	$839	$1,396	$1,616

Location (Climate Zone) T_{Clg} = 24.4 °C	Total Annual Energy Cost Including Societal Cost of Capital ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$778	$588	$691	$1,061	$1,270
Arcata, CA (Marine)	$705	$466	$467	$776	$1,014
Austin, TX (Hot-Humid)	$707	$425	$697	$1,220	$1,448
Buffalo, NY (Cold)	$1,335	$1,044	$1,115	$1,602	$1,933
Fairbanks, AK (Sub-Artic)	$2,594	$2,140	$2,150	$2,770	$3,321
Houghton, MI (Very Cold)	$1,431	$1,141	$1,175	$1,592	$1,924
Los Angeles, CA (Hot-Dry)	$477	$311	$371	$670	$856
Knoxville, TN (Mixed-Humid)	$744	$500	$638	$1,025	$1,236
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.4: WC-2 Energy Cost w SCC Savings from DC mAER, T_{Clg}=24.4 °C

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Value of Energy Savings using Scenario with Demand Controlled mAER vs. Base Case with Constant mAER ($/y) Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$0	$0	$237	$420	$430
Arcata, CA (Marine)	$0	$0	$329	$679	$705
Austin, TX (Hot-Humid)	$0	$0	$139	$216	$222
Buffalo, NY (Cold)	$0	$0	$448	$850	$875
Fairbanks, AK (Sub-Artic)	$0	$0	$765	$1,683	$1,739
Houghton, MI (Very Cold)	$0	$0	$441	$921	$946
Los Angeles, CA (Hot-Dry)	$0	$0	$187	$357	$375
Knoxville, TN (Mixed-Humid)	$0	$0	$201	$370	$381
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.5: WC-2 Non-Cap. Cost w DALYs: C mAER, T_{Clg}=24.4 °C

Location (Climate Zone) T_{Clg} = 24.4 °C		Total Annual Non-Capital Monetized Cost - Constant mAER ($/y) ASHRAE 62.2-2016 Min mAER	Constant mAER CHCHO,i,n ≤ 81 ppb	Constant mAER CHCHO,i,n ≤ 40 ppb	Constant mAER CHCHO,i,n ≤ 16 ppb	Constant mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$865	***$699***	$993	$1,499	$1,709
	68% Upper CI Annual Value of DALYs lost -	$1,561	$1,587	***$1,521***	$1,643	$1,781
	95% Upper CI Annual Value of DALYs lost -	$7,245	$8,839	$5,833	$2,819	***$2,369***
Arcata, CA (Marine)	Median Annual Value of DALYs	$762	***$553***	$841	$1,458	$1,719
	68% Upper CI Annual Value of DALYs lost -	$1,218	$1,249	***$1,201***	$1,482	$1,719
	95% Upper CI Annual Value of DALYs lost -	$4,942	$6,933	$4,141	***$1,678***	$1,719
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$809	***$563***	$923	$1,463	$1,682
	68% Upper CI Annual Value of DALYs lost -	$1,625	$1,667	***$1,619***	$1,679	$1,778
	95% Upper CI Annual Value of DALYs lost -	$8,289	$10,683	$7,303	$3,443	***$2,562***
Buffalo, NY (Cold)	Median Annual Value of DALYs lost - Family of 4	$1,410	***$1,143***	$1,621	$2,464	$2,818
	68% Upper CI Annual Value of DALYs lost - Family of 4	$2,010	***$1,935***	$2,077	$2,560	$2,890
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,910	$8,403	$5,801	***$3,344***	$3,478
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs lost - Family of 4	$2,654	***$2,224***	$2,960	$4,459	$5,063
	68% Upper CI Annual Value of DALYs lost - Family of 4	$3,134	***$2,896***	$3,320	$4,507	$5,087
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,054	$8,384	$6,260	***$4,899***	$5,283
Houghton, MI (Very Cold)	Median Annual Value of DALYs lost - Family of 4	$1,497	***$1,231***	$1,666	$2,520	$2,873
	68% Upper CI Annual Value of DALYs lost - Family of 4	$2,025	***$1,951***	$2,074	$2,568	$2,897
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,337	$7,831	$5,406	***$2,960***	$3,093
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$564	***$431***	$627	$1,043	$1,240
	68% Upper CI Annual Value of DALYs lost -	$1,260	$1,391	$1,179	***$1,163***	$1,312
	95% Upper CI Annual Value of DALYs lost -	$6,944	$9,231	$5,687	$2,143	***$1,900***
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$828	***$617***	$911	$1,414	$1,622
	68% Upper CI Annual Value of DALYs lost -	$1,500	$1,553	***$1,487***	$1,558	$1,670
	95% Upper CI Annual Value of DALYs lost -	$6,988	$9,197	$6,191	$2,734	***$2,062***
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$***	Minimum cost for DALY risk level	

Table I.6: WC-2 Non-Cap. Cost w DALYs: DC mAER, T_{Clg}=24.4 °C

Location (Climate Zone) T_{Clg} = 24.4 °C		Total Annual Non-Capital Monetized Cost - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$865	***$699***	$787	$1,106	$1,291
	68% Upper CI Annual Value of DALYs lost -	$1,561	$1,587	$1,555	$1,466	***$1,459***
	95% Upper CI Annual Value of DALYs lost -	$7,245	$8,839	$7,827	$4,406	***$2,831***
Arcata, CA (Marine)	Median Annual Value of DALYs	$762	***$553***	$554	$824	$1,035
	68% Upper CI Annual Value of DALYs lost -	$1,218	$1,249	$1,250	$1,208	***$1,203***
	95% Upper CI Annual Value of DALYs lost -	$4,942	$6,933	$6,934	$4,344	***$2,575***
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$809	***$563***	$784	$1,247	$1,460
	68% Upper CI Annual Value of DALYs lost -	$1,625	$1,667	$1,480	***$1,463***	$1,556
	95% Upper CI Annual Value of DALYs lost -	$8,289	$10,683	$7,164	$3,227	***$2,340***
Buffalo, NY (Cold)	Median Annual Value of DALYs	$1,410	***$1,143***	$1,205	$1,647	$1,954
	68% Upper CI Annual Value of DALYs lost -	$2,010	$1,935	***$1,925***	$2,007	$2,122
	95% Upper CI Annual Value of DALYs lost -	$6,910	$8,403	$7,805	$4,947	***$3,494***
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	$2,654	***$2,224***	$2,231	$2,815	$3,339
	68% Upper CI Annual Value of DALYs lost -	$3,134	$2,896	***$2,879***	$3,175	$3,483
	95% Upper CI Annual Value of DALYs lost -	$7,054	$8,384	$8,171	$6,115	***$4,659***
Houghton, MI (Very Cold)	Median Annual Value of DALYs	$1,497	***$1,231***	$1,259	$1,637	$1,942
	68% Upper CI Annual Value of DALYs lost -	$2,025	$1,951	***$1,931***	$1,997	$2,086
	95% Upper CI Annual Value of DALYs lost -	$6,337	$7,831	$7,419	$4,937	***$3,262***
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$564	***$431***	$479	$718	$877
	68% Upper CI Annual Value of DALYs lost -	$1,260	$1,391	$1,343	$1,102	***$1,045***
	95% Upper CI Annual Value of DALYs lost -	$6,944	$9,231	$8,399	$4,238	***$2,417***
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$828	***$617***	$737	$1,073	$1,257
	68% Upper CI Annual Value of DALYs lost -	$1,500	$1,553	$1,529	$1,457	***$1,425***
	95% Upper CI Annual Value of DALYs lost -	$6,988	$9,197	$7,997	$4,593	***$2,797***
Cell Legend:		(shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate		***$$$*** Minimum cost for DALY risk level		

Table I.7: WC-2 Non-Cap. Cost Savings from DC mAER, T_{Clg}=24.4 ^{o}C

Location	(Climate Zone) T_{Clg} = 24.4 ^{o}C	Total Annual Non-Capital Monetized Savings - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$0	$0	$207	$393	$418
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$33	$177	$322
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$1,993	-$1,587	-$462
Arcata, CA (Marine)	Median Annual Value of DALYs	$0	$0	$287	$634	$684
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$49	$274	$516
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$2,793	-$2,666	-$856
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$0	$0	$139	$216	$222
	68% Upper CI Annual Value of DALYs lost -	$0	$0	$139	$216	$222
	95% Upper CI Annual Value of DALYs lost -	$0	$0	$139	$216	$222
Buffalo, NY (Cold)	Median Annual Value of DALYs	$0	$0	$415	$817	$863
	68% Upper CI Annual Value of DALYs lost -	$0	$0	$151	$553	$767
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$2,005	-$1,603	-$17
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	$0	$0	$729	$1,644	$1,724
	68% Upper CI Annual Value of DALYs lost -	$0	$0	$441	$1,332	$1,604
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$1,911	-$1,216	$624
Houghton, MI (Very Cold)	Median Annual Value of DALYs	$0	$0	$408	$882	$931
	68% Upper CI Annual Value of DALYs lost -	$0	$0	$144	$570	$811
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$2,012	-$1,978	-$169
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$0	$0	$148	$324	$363
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$164	$60	$267
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$2,712	-$2,096	-$517
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$0	$0	$174	$340	$366
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$42	$100	$246
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$1,806	-$1,860	-$734
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate		$$$ Savings		

Table I.8: WC-3 Thermal Energy Summary: C/DC mAER, T_{Clg}=24.4 ^oC

Location (Climate Zone) T_{Clg} = 24.4 ^oC	Annual Thermal Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	66.7	18,528	63.2	92.2	25,611	87.4	158.1	43,917	149.9	172.1	47,806	163.1	177.5	49,306	168.2
Arcata, CA (Marine)	33.9	9,417	32.1	59.1	16,417	56.0	116.2	32,278	110.1	129.9	36,084	123.1	135.1	37,528	128.1
Austin, TX (Hot-Humid)	62.3	17,306	59.0	100.6	27,945	95.4	179.7	49,917	170.3	199	55,278	188.6	206.4	57,334	195.6
Buffalo, NY (Cold)	89.4	24,834	84.7	118.7	32,972	112.5	202.4	56,223	191.8	219.2	60,889	207.8	225.6	62,667	213.8
Fairbanks, AK (Sub -Artic)	171.3	47,584	162.4	215.8	59,945	204.5	355	98,612	336.5	380.7	105,751	360.8	390.6	108,501	370.2
Houghton, MI (Very Cold)	137.2	38,111	130.0	207.9	57,750	197.1	371.2	103,112	351.8	405.5	112,640	384.3	418.6	116,279	396.8
Los Angeles, CA (Hot-Dry)	23.0	6,389	21.8	33.4	9,278	31.7	74.9	20,806	71.0	85.7	23,806	81.2	89.8	24,945	85.1
Knoxville, TN (Mixed-Humid)	65.2	18,111	61.8	98	27,222	92.9	173	48,056	164.0	190.6	52,945	180.7	197.4	54,834	187.1

Location (Climate Zone) T_{Clg} = 24.4 ^oC	Annual Thermal Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	66.7	18,528	63.2	100.5	27,917	95.3	110.8	30,778	105.0	119.5	33,195	113.3	123.7	34,361	117.2
Arcata, CA (Marine)	33.9	9,417	32.1	47.6	13,222	45.1	57.7	16,028	54.7	71.0	19,722	67.3	76.3	21,195	72.3
Austin, TX (Hot-Humid)	62.3	17,306	59.0	123.1	34,195	116.7	152.4	42,334	144.4	171.6	47,667	162.6	179	49,723	169.7
Buffalo, NY (Cold)	89.4	24,834	84.7	129.9	36,084	123.1	137.8	38,278	130.6	145.6	40,445	138.0	149.4	41,500	141.6
Fairbanks, AK (Sub -Artic)	171.3	47,584	162.4	238.8	66,334	226.3	243.5	67,639	230.8	249.5	69,306	236.5	252.7	70,195	239.5
Houghton, MI (Very Cold)	137.2	38,111	130.0	221	61,389	209.5	243.7	67,695	231.0	264.4	73,445	250.6	274	76,112	259.7
Los Angeles, CA (Hot-Dry)	23	6,389	21.8	32.1	8,917	30.4	46.9	13,028	44.5	57.7	16,028	54.7	61.9	17,195	58.7
Knoxville, TN (Mixed-Humid)	65.2	18,111	61.8	108.7	30,195	103.0	126.3	35,084	119.7	140.6	39,056	133.3	146.8	40,778	139.1

Location (Climate Zone) T_{Clg} = 24.4 ^oC	% Energy Savings from Demand Controlled vs. Constant mAER						
				$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
					House + Venitilation	House + Venitilation	House + Venitilation
				%	%	%	%
Amarillo, TX (Mixed-Dry)				-9%	30%	31%	30%
Arcata, CA (Marine)				19%	50%	45%	44%
Austin, TX (Hot-Humid)				-22%	15%	14%	13%
Buffalo, NY (Cold)				-9%	32%	34%	34%
Fairbanks, AK (Sub -Artic)				-11%	31%	34%	35%
Houghton, MI (Very Cold)				-6%	34%	35%	35%
Los Angeles, CA (Hot-Dry)				4%	37%	33%	31%
Knoxville, TN (Mixed-Humid)				-11%	27%	26%	26%
Average All Zones				-6%	32%	31%	31%

[a] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.

Cell Legend: (shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate

Table I.9: WC-3 mAER and C_{HCHO} Summary: C/DC mAER, T_{Clg}=24.4 ^{o}C

Location (Climate Zone) T_{Clg} = 24.4 ^{o}C	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER CHCHO,i,n ≤ 81 ppb			Constant mAER CHCHO,i,n ≤ 40 ppb			Constant mAER CHCHO,i,n ≤ 16 ppb			Constant mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.084	196	65	0.517	81	20	0.669	40	7	0.758	16	3	0.792	7	2
Arcata, CA (Marine)	0.112	173	53	0.488	81	1	0.643	40	1	0.733	16	1	0.767	7	1
Austin, TX (Hot-Humid)	0.149	181	115	0.519	81	43	0.670	40	18	0.759	16	6	0.793	7	3
Buffalo, NY (Cold)	0.090	192	56	0.515	81	16	0.668	40	6	0.757	16	3	0.791	7	2
Fairbanks, AK (Sub -Artic)	0.084	196	38	0.512	81	7	0.664	40	2	0.753	16	1	0.786	7	1
Houghton, MI (Very Cold)	0.085	194	45	0.510	81	10	0.662	40	3	0.751	16	1	0.784	7	1
Los Angeles, CA (Hot-Dry)	0.147	175	94	0.509	81	24	0.662	40	7	0.752	16	2	0.786	7	2
Knoxville, TN (Mixed-Humid)	0.144	181	89	0.514	81	30	0.666	40	13	0.755	16	4	0.788	7	2
Location (Climate Zone) T_{Clg} = 24.4 ^{o}C	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER CHCHO,i,n ≤ 81 ppb			Demand Controlled mAER CHCHO,i,n ≤ 40 ppb			Demand Controlled mAER CHCHO,i,n ≤ 16 ppb			Demand Controlled mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.084	196	65	0.138	81	47	0.249	40	28	0.343	16	13	0.386	7	6
Arcata, CA (Marine)	0.112	173	53	0.017	81	57	0.184	40	38	0.317	16	16	0.362	7	7
Austin, TX (Hot-Humid)	0.149	181	115	0.305	81	72	0.466	40	38	0.570	16	16	0.608	7	7
Buffalo, NY (Cold)	0.090	192	56	0.109	81	41	0.199	40	25	0.284	16	12	0.320	7	6
Fairbanks, AK (Sub -Artic)	0.084	196	38	0.058	81	31	0.128	40	20	0.197	16	9	0.228	7	4
Houghton, MI (Very Cold)	0.085	194	45	0.079	81	35	0.154	40	23	0.234	16	11	0.270	7	5
Los Angeles, CA (Hot-Dry)	0.147	175	94	0.200	81	75	0.392	40	40	0.496	16	16	0.533	7	7
Knoxville, TN (Mixed-Humid)	0.144	181	89	0.212	81	60	0.341	40	35	0.449	16	15	0.492	7	7
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Table I.10: WC-3 Total Energy Cost w SCC: C/DC mAER, T_{Clg}=24.4 ^oC

Location (Climate Zone) TClg = 24.4 oC	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$665	$1,141	$1,837	$2,016	$2,085
Arcata, CA (Marine)	$488	$1,053	$1,853	$2,081	$2,167
Austin, TX (Hot-Humid)	$581	$1,085	$1,803	$2,006	$2,084
Buffalo, NY (Cold)	$1,224	$1,924	$3,122	$3,406	$3,515
Fairbanks, AK (Sub-Artic)	$2,645	$3,679	$5,899	$6,362	$6,538
Houghton, MI (Very Cold)	$1,598	$2,666	$4,601	$5,044	$5,212
Los Angeles, CA (Hot-Dry)	$361	$729	$1,303	$1,487	$1,557
Knoxville, TN (Mixed-Humid)	$608	$1,063	$1,755	$1,944	$2,016
Location (Climate Zone) T_{Clg} = 24.4 ^oC	Total Annual Energy Cost Including Societal Cost of Capital ($)				
	Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$665	$1,009	$1,166	$1,298	$1,361
Arcata, CA (Marine)	$488	$589	$827	$1,080	$1,175
Austin, TX (Hot-Humid)	$581	$1,154	$1,476	$1,685	$1,765
Buffalo, NY (Cold)	$1,224	$1,763	$1,933	$2,098	$2,174
Fairbanks, AK (Sub-Artic)	$2,645	$3,636	$3,767	$3,916	$3,990
Houghton, MI (Very Cold)	$1,598	$2,538	$2,841	$3,125	$3,256
Los Angeles, CA (Hot-Dry)	$361	$501	$800	$994	$1,067
Knoxville, TN (Mixed-Humid)	$608	$999	$1,208	$1,380	$1,452
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.11: WC-2 Energy Cost w SCC Savings from DC mAER, T_{Clg}=24.4 ^oC

Location (Climate Zone) T_{Clg} = 24.4 ^oC	Annual Value of Energy Savings using Scenario with Demand Controlled mAER vs. Base Case with Constant mAER ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$0	$133	$671	$718	$724
Arcata, CA (Marine)	$0	$464	$1,026	$1,001	$992
Austin, TX (Hot-Humid)	$0	($69)	$328	$321	$319
Buffalo, NY (Cold)	$0	$161	$1,189	$1,309	$1,341
Fairbanks, AK (Sub-Artic)	$0	$42	$2,133	$2,446	$2,548
Houghton, MI (Very Cold)	$0	$128	$1,760	$1,919	$1,956
Los Angeles, CA (Hot-Dry)	$0	$228	$503	$493	$490
Knoxville, TN (Mixed-Humid)	$0	$64	$546	$564	$564
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.12: WC-3 Non-Cap. Cost w DALYs: C mAER, T_{Clg}=24.4 °C

	Location (Climate Zone) T_{Clg} = 24.4 °C	Total Annual Non-Capital Monetized Cost - Constant mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Constant mAER CHCHO,i,n ≤ 81 ppb+J66	Constant mAER CHCHO,i,n ≤ 40 ppb	Constant mAER CHCHO,i,n ≤ 16 ppb	Constant mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	***$860***	$1,201	$1,858	$2,025	$2,091
	68% Upper CI Annual Value of DALYs lost -	$2,420	***$1,681***	$2,026	$2,097	$2,139
	95% Upper CI Annual Value of DALYs lost -	$15,160	$5,601	$3,398	$2,685	***$2,531***
Arcata, CA (Marine)	Median Annual Value of DALYs	***$647***	$1,056	$1,856	$2,084	$2,170
	68% Upper CI Annual Value of DALYs lost -	$1,919	***$1,080***	$1,880	$2,108	$2,194
	95% Upper CI Annual Value of DALYs lost -	$12,307	***$1,276***	$2,076	$2,304	$2,390
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	***$926***	$1,214	$1,857	$2,024	$2,093
	68% Upper CI Annual Value of DALYs lost -	$3,686	$2,246	$2,289	$2,168	***$2,165***
	95% Upper CI Annual Value of DALYs lost -	$26,226	$10,674	$5,817	$3,344	***$2,753***
Buffalo, NY (Cold)	Median Annual Value of DALYs lost - Family of 4	***$1,392***	$1,972	$3,140	$3,415	$3,521
	68% Upper CI Annual Value of DALYs lost - Family of 4	$2,736	***$2,356***	$3,284	$3,487	$3,569
	95% Upper CI Annual Value of DALYs lost - Family of 4	$13,712	$5,492	$4,460	$4,075	***$3,961***
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs lost - Family of 4	***$2,759***	$3,700	$5,905	$6,365	$6,541
	68% Upper CI Annual Value of DALYs lost - Family of 4	***$3,671***	$3,868	$5,953	$6,389	$6,565
	95% Upper CI Annual Value of DALYs lost - Family of 4	$11,119	***$5,240***	$6,345	$6,585	$6,761
Houghton, MI (Very Cold)	Median Annual Value of DALYs lost - Family of 4	***$1,733***	$2,696	$4,610	$5,047	$5,215
	68% Upper CI Annual Value of DALYs lost - Family of 4	***$2,813***	$2,936	$4,682	$5,071	$5,239
	95% Upper CI Annual Value of DALYs lost - Family of 4	$11,633	$4,896	$5,270	***$5,267***	$5,435
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	***$643***	$801	$1,324	$1,493	$1,563
	68% Upper CI Annual Value of DALYs lost -	$2,899	***$1,377***	$1,492	$1,541	$1,611
	95% Upper CI Annual Value of DALYs lost -	$21,323	$6,081	$2,864	***$1,933***	$2,003
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	***$875***	$1,153	$1,794	$1,956	$2,022
	68% Upper CI Annual Value of DALYs lost -	$3,011	***$1,873***	$2,106	$2,052	$2,070
	95% Upper CI Annual Value of DALYs lost -	$20,455	$7,753	$4,654	$2,836	***$2,462***
Cell Legend:			mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$***	Minimum cost for DALY risk level	

Table I.13: WC-3 Non-Cap. Cost w DALYs: DC mAER, T_{Clg}=24.4 ºC

Location (Climate Zone) T_{Clg} = 24.4 °C		Total Annual Non-Capital Monetized Cost - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	***$860***	$1,150	$1,250	$1,337	$1,379
	68% Upper CI Annual Value of DALYs lost -	$2,420	$2,278	$1,922	$1,649	***$1,523***
	95% Upper CI Annual Value of DALYs lost -	$15,160	$11,490	$7,410	$4,197	***$2,699***
Arcata, CA (Marine)	Median Annual Value of DALYs	***$647***	$760	$941	$1,128	$1,196
	68% Upper CI Annual Value of DALYs lost -	$1,919	$2,128	$1,853	$1,512	***$1,364***
	95% Upper CI Annual Value of DALYs lost -	$12,307	$13,300	$9,301	$4,648	***$2,736***
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	***$926***	$1,370	$1,590	$1,733	$1,786
	68% Upper CI Annual Value of DALYs lost -	$3,686	$3,098	$2,502	$2,117	***$1,954***
	95% Upper CI Annual Value of DALYs lost -	$26,226	$17,210	$9,950	$5,253	***$3,326***
Buffalo, NY (Cold)	Median Annual Value of DALYs	***$1,392***	$1,886	$2,008	$2,134	$2,192
	68% Upper CI Annual Value of DALYs lost -	$2,736	$2,870	$2,608	$2,422	***$2,336***
	95% Upper CI Annual Value of DALYs lost -	$13,712	$10,906	$7,508	$4,774	***$3,512***
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	***$2,759***	$3,729	$3,827	$3,943	$4,002
	68% Upper CI Annual Value of DALYs lost -	$3,671	$4,473	$4,307	$4,159	***$4,098***
	95% Upper CI Annual Value of DALYs lost -	$11,119	$10,549	$8,227	$5,923	***$4,882***
Houghton, MI (Very Cold)	Median Annual Value of DALYs	***$1,733***	$2,643	$2,910	$3,158	$3,271
	68% Upper CI Annual Value of DALYs lost -	$2,813	$3,483	$3,462	$3,422	***$3,391***
	95% Upper CI Annual Value of DALYs lost -	$11,633	$10,343	$7,970	$5,578	***$4,371***
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	***$643***	$726	$920	$1,042	$1,088
	68% Upper CI Annual Value of DALYs lost -	$2,899	$2,526	$1,880	$1,426	***$1,256***
	95% Upper CI Annual Value of DALYs lost -	$21,323	$17,226	$9,720	$4,562	***$2,628***
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	***$875***	$1,179	$1,313	$1,425	$1,473
	68% Upper CI Annual Value of DALYs lost -	$3,011	$2,619	$2,153	$1,785	***$1,641***
	95% Upper CI Annual Value of DALYs lost -	$20,455	$14,379	$9,013	$4,725	***$3,013***
Cell Legend:			mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$***	Minimum cost for DALY risk level	

Table I.14: WC-3 Non-Cap. Cost Savings from DC mAER, T_{Clg}=24.4 °C

	Location (Climate Zone) T_{Clg} = 24.4 °C	Total Annual Non-Capital Monetized Savings - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$0	$52	$608	$688	$712
	68% Upper CI Annual Value of DALYs lost -	$0	-$596	$104	$448	$616
	95% Upper CI Annual Value of DALYs lost -	$0	-$5,888	-$4,012	-$1,512	-$168
Arcata, CA (Marine)	Median Annual Value of DALYs	$0	$296	$915	$956	$974
	68% Upper CI Annual Value of DALYs lost -	$0	-$1,048	$27	$596	$830
	95% Upper CI Annual Value of DALYs lost -	$0	-$12,024	-$7,225	-$2,344	-$346
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$0	-$156	$268	$291	$307
	68% Upper CI Annual Value of DALYs lost -	$0	-$852	-$212	$51	$211
	95% Upper CI Annual Value of DALYs lost -	$0	-$6,536	-$4,132	-$1,909	-$573
Buffalo, NY (Cold)	Median Annual Value of DALYs	$0	$86	$1,132	$1,282	$1,329
	68% Upper CI Annual Value of DALYs lost -	$0	-$514	$676	$1,066	$1,233
	95% Upper CI Annual Value of DALYs lost -	$0	-$5,414	-$3,048	-$698	$449
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	$0	-$30	$2,079	$2,422	$2,539
	68% Upper CI Annual Value of DALYs lost -	$0	-$606	$1,647	$2,230	$2,467
	95% Upper CI Annual Value of DALYs lost -	$0	-$5,310	-$1,881	$662	$1,879
Houghton, MI (Very Cold)	Median Annual Value of DALYs	$0	$53	$1,700	$1,889	$1,944
	68% Upper CI Annual Value of DALYs lost -	$0	-$547	$1,220	$1,649	$1,848
	95% Upper CI Annual Value of DALYs lost -	$0	-$5,447	-$2,700	-$311	$1,064
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$0	$75	$404	$451	$475
	68% Upper CI Annual Value of DALYs lost -	$0	-$1,149	-$388	$115	$355
	95% Upper CI Annual Value of DALYs lost -	$0	-$11,145	-$6,856	-$2,629	-$625
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$0	-$26	$480	$531	$549
	68% Upper CI Annual Value of DALYs lost -	$0	-$746	-$48	$267	$429
	95% Upper CI Annual Value of DALYs lost -	$0	-$6,626	-$4,360	-$1,889	-$551
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	$$$ Savings		

Table I.15: WC-2 Thermal Energy Summary: C and DC mAER, T_{Clg}=23.4 °C

Location (Climate Zone) T_{Clg} = 23.4 °C	Annual Thermal Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	80.5	22.4	76.3	67.6	18.8	64.1	77.4	21.5	73.4	119.6	33.2	113.4	137.3	38.1	130.1
Arcata, CA (Marine)	49.7	13.8	47.1	38.7	10.8	36.7	44.4	12.3	42.1	78.7	21.9	74.6	94.4	26.2	89.5
Austin, TX (Hot-Humid)	85.0	23.6	80.6	58.6	16.3	55.5	75.9	21.1	71.9	134.5	37.4	127.5	157.9	43.9	149.7
Buffalo, NY (Cold)	97.5	27.1	92.4	83.1	23.1	78.8	94	26.1	89.1	143.6	39.9	136.1	164.9	45.8	156.3
Fairbanks, AK (Sub -Artic)	165.9	46.1	157.2	143.5	39.9	136.0	156.4	43.4	148.2	235.4	65.4	223.1	269.5	74.9	255.4
Houghton, MI (Very Cold)	121.5	33.8	115.2	103.5	28.8	98.1	113.7	31.6	107.8	173.1	48.1	164.1	198.7	55.2	188.3
Los Angeles, CA (Hot-Dry)	36.9	10.3	35.0	31.1	8.6	29.5	34.5	9.6	32.7	55.9	15.5	53.0	67	18.6	63.5
Knoxville, TN (Mixed-Humid)	86.2	23.9	81.7	64.9	18.0	61.5	72.7	20.2	68.9	122.7	34.1	116.3	143.7	39.9	136.2

Location (Climate Zone) T_{Clg} = 23.4 °C	Annual Thermal Energy Use [(GJ/kWh_{th}/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y	GJ/y	kWh_{th}/y	MBTU/y
Amarillo, TX (Mixed-Dry)	80.5	22.4	76.3	67.6	18.8	64.1	70.9	19.7	67.2	96.6	26.8	91.6	114.1	31.7	108.1
Arcata, CA (Marine)	49.7	13.8	47.1	38.7	10.8	36.7	38.7	10.8	36.7	52.1	14.5	49.4	66.3	18.4	62.8
Austin, TX (Hot-Humid)	85.0	23.6	80.6	58.6	16.3	55.5	85.0	23.6	80.6	122.8	34.1	116.4	145.8	40.5	138.2
Buffalo, NY (Cold)	97.5	27.1	92.4	83.1	23.1	78.8	84.8	23.6	80.4	107.7	29.9	102.1	128.8	35.8	122.1
Fairbanks, AK (Sub -Artic)	165.9	46.1	157.2	143.5	39.9	136.0	143.5	39.9	136.0	166.7	46.3	158.0	201.2	55.9	190.7
Houghton, MI (Very Cold)	121.5	33.8	115.2	103.5	28.8	98.1	104.4	29.0	99.0	126.1	35.0	119.5	151.8	42.2	143.9
Los Angeles, CA (Hot-Dry)	36.9	10.3	35.0	31.1	8.6	29.5	32.2	8.9	30.5	44.1	12.3	41.8	54.1	15.0	51.3
Knoxville, TN (Mixed-Humid)	86.2	23.9	81.7	64.9	18.0	61.5	70.7	19.6	67.0	105.3	29.3	99.8	125.9	35.0	119.3

Location (Climate Zone) T_{Clg} = 23.4 °C	% Energy Savings from Demand Controlled vs. Constant mAER						
				$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
					House + Venitilation	House + Venitilation	House + Venitilation
				%	%	%	%
Amarillo, TX (Mixed-Dry)				0%	8%	19%	17%
Arcata, CA (Marine)				0%	13%	34%	30%
Austin, TX (Hot-Humid)				0%	-12%	9%	8%
Buffalo, NY (Cold)				0%	10%	25%	22%
Fairbanks, AK (Sub -Artic)				0%	8%	29%	25%
Houghton, MI (Very Cold)				0%	8%	27%	24%
Los Angeles, CA (Hot-Dry)				0%	7%	21%	19%
Knoxville, TN (Mixed-Humid)				0%	3%	14%	12%
Average All Zones				0%	6%	22%	20%

[a] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.

Cell Legend: (shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate

Table I.16: WC-2 mAER and C_{HCHO} Summary: C/DC mAER, T_{Clg}=23.4 ºC

Location (Climate Zone) T_{Clg} = 23.4 °C	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.145	37.9	26.0	0	50.0	34.0	0.122	40.0	27.5	0.387	16.0	6.9	0.487	7.0	3.3
Arcata, CA (Marine)	0.154	35.3	19.0	0	47.2	28.8	0.101	40.0	23.4	0.369	16.0	1.2	0.469	7.0	7.0
Austin, TX (Hot-Humid)	0.166	36.0	28.8	0	50.9	40.3	0.122	40.0	32.6	0.388	16.0	10.0	0.487	7.0	4.2
Buffalo, NY (Cold)	0.147	37.7	23.1	0	50.0	31.2	0.122	40.0	25.1	0.387	16.0	5.2	0.487	7.0	2.8
Fairbanks, AK (Sub -Artic)	0.144	36.4	19.7	0	49.2	27.3	0.104	40.0	22.6	0.370	16.0	2.3	0.470	7.0	0.9
Houghton, MI (Very Cold)	0.146	36.2	20.4	0	49.2	28.2	0.104	40.0	23.5	0.370	16.0	3.2	0.470	7.0	1.1
Los Angeles, CA (Hot-Dry)	0.165	36.1	25.8	0	50.0	37.2	0.122	40.0	29.6	0.387	16.0	7.1	0.487	7.0	2.9
Knoxville, TN (Mixed-Humid)	0.164	35.0	24.5	0	49.7	35.5	0.084	40.0	29.1	0.351	16.0	6.9	0.450	7.0	2.8

Location (Climate Zone) T_{Clg} = 23.4 °C	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb			Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Amarillo, TX (Mixed-Dry)	0.145	38.0	26.0	0	50.0	33.5	0.035	40.0	31.7	0.269	16.0	16.0	0.369	7.0	7.0
Arcata, CA (Marine)	0.154	35.3	19.0	0	47.2	28.8	0.001	40.0	28.7	0.195	16.0	16.0	0.295	7.0	7.0
Austin, TX (Hot-Humid)	0.166	36.0	28.8	0	50.9	40.3	0.065	40.0	36.1	0.313	16.0	16.0	0.413	7.0	7.0
Buffalo, NY (Cold)	0.147	37.7	23.1	0	50.0	31.2	0.023	40.0	29.8	0.241	16.0	16.0	0.342	7.0	7.0
Fairbanks, AK (Sub -Artic)	0.144	36.4	19.7	0	49.2	27.3	0.008	40.0	26.8	0.202	16.0	16.0	0.302	7.0	7.0
Houghton, MI (Very Cold)	0.146	36.2	20.4	0	49.2	28.2	0.012	40.0	27.5	0.212	16.0	16.0	0.312	7.0	7.0
Los Angeles, CA (Hot-Dry)	0.165	36.1	25.8	0	50.0	37.2	0.035	40.0	35.2	0.278	16.0	16.0	0.378	7.0	7.0
Knoxville, TN (Mixed-Humid)	0.164	35.0	24.5	0	49.7	35.5	0.038	40.0	32.9	0.264	16.0	16.0	0.364	7.0	7.0
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Table I.17: WC-2 Energy Cost w SCC: C/DC mAER, T_{Clg}=23.4 ^oC

Location (Climate Zone) T_{Clg} = 23.4 ^oC	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$827	$627	$786	$1,324	$1,543
Arcata, CA (Marine)	$709	$469	$608	$1,209	$1,468
Austin, TX (Hot-Humid)	$774	$473	$677	$1,290	$1,531
Buffalo, NY (Cold)	$1,372	$1,075	$1,308	$2,149	$2,500
Fairbanks, AK (Sub-Artic)	$2,615	$2,155	$2,438	$3,852	$4,450
Houghton, MI (Very Cold)	$1,461	$1,165	$1,346	$2,185	$2,537
Los Angeles, CA (Hot-Dry)	$531	$351	$474	$899	$1,093
Knoxville, TN (Mixed-Humid)	$790	$533	$639	$1,184	$1,406

Location (Climate Zone) T_{Clg} = 23.4 ^oC	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$827	$627	$677	$1,045	$1,263
Arcata, CA (Marine)	$709	$469	$470	$766	$1,008
Austin, TX (Hot-Humid)	$774	$473	$720	$1,156	$1,394
Buffalo, NY (Cold)	$1,372	$1,075	$1,114	$1,575	$1,924
Fairbanks, AK (Sub-Artic)	$2,615	$2,155	$2,162	$2,676	$3,280
Houghton, MI (Very Cold)	$1,461	$1,165	$1,183	$1,555	$1,908
Los Angeles, CA (Hot-Dry)	$531	$351	$388	$690	$872
Knoxville, TN (Mixed-Humid)	$790	$533	$600	$997	$1,217
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.18: WC-2 Energy Cost w SCC Savings from DC mAER, T_{Clg}=23.4 ^oC

Location (Climate Zone) T_{Clg} = 23.4 ^oC	Annual Value of Energy Savings using Scenario with Demand Controlled mAER vs. Base Case with Constant mAER ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	$0	$0	$108	$279	$281
Arcata, CA (Marine)	$0	$0	$138	$443	$461
Austin, TX (Hot-Humid)	$0	$0	($43)	$134	$137
Buffalo, NY (Cold)	$0	$0	$194	$574	$576
Fairbanks, AK (Sub-Artic)	$0	$0	$276	$1,175	$1,169
Houghton, MI (Very Cold)	$0	$0	$164	$630	$629
Los Angeles, CA (Hot-Dry)	$0	$0	$86	$209	$221
Knoxville, TN (Mixed-Humid)	$0	$0	$39	$187	$189
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.19: WC-2 Energy Cost Savings from C mAER, T_{Clg}=23.4 vs. 24.4 °C

Location (Climate Zone)	Annual Value of Energy Savings from T_{clg} = 23.4 vs. 24.4 °C				
	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	($49)	($39)	$142	$157	$157
Arcata, CA (Marine)	($4)	($4)	$188	$246	$251
Austin, TX (Hot-Humid)	($67)	($48)	$159	$146	$139
Buffalo, NY (Cold)	($38)	($31)	$256	$303	$309
Fairbanks, AK (Sub-Artic)	($21)	($15)	$477	$601	$610
Houghton, MI (Very Cold)	($29)	($24)	$269	$329	$333
Los Angeles, CA (Hot-Dry)	($54)	($41)	$84	$129	$138
Knoxville, TN (Mixed-Humid)	($46)	($33)	$199	$212	$210
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.20: WC-2 Energy Cost Savings from DC mAER, T_{Clg}=23.4 vs. 24.4 °C

Location (Climate Zone)	Annual Value of Energy Savings from T_{clg} = 23.4 vs. 24.4 °C				
	Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	($49)	($39)	$14	$16	$7
Arcata, CA (Marine)	($4)	($4)	($3)	$10	$7
Austin, TX (Hot-Humid)	($67)	($48)	($23)	$64	$53
Buffalo, NY (Cold)	($38)	($31)	$1	$27	$9
Fairbanks, AK (Sub-Artic)	($21)	($15)	($12)	$93	$41
Houghton, MI (Very Cold)	($29)	($24)	($8)	$38	$16
Los Angeles, CA (Hot-Dry)	($54)	($41)	($17)	($20)	($16)
Knoxville, TN (Mixed-Humid)	($46)	($33)	$38	$28	$19
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate			

Table I.21: WC-2 Non-Cap. Cost w DALYs: C mAER, T_{Clg}=23.4 °C

	Location (Climate Zone) T_{Clg} = 23.4 °C	Total Annual Non-Capital Monetized Cost - Constnat mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Constant mAER CHCHO,i,n ≤ 81 ppb	Constant mAER CHCHO,i,n ≤ 40 ppb	Constant mAER CHCHO,i,n ≤ 16 ppb	Constant mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$159	***$103***	$151	$236	$281
	68% Upper CI Annual Value of DALYs lost -	$783	$919	$811	$402	***$360***
	95% Upper CI Annual Value of DALYs lost -	$5,879	$7,583	$6,201	$1,754	***$1,007***
Arcata, CA (Marine)	Median Annual Value of DALYs	$164	***$87***	$140	$259	$346
	68% Upper CI Annual Value of DALYs lost -	$620	$778	$702	***$288***	$514
	95% Upper CI Annual Value of DALYs lost -	$4,344	$6,423	$5,288	***$523***	$1,886
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$174	***$121***	$163	$235	$270
	68% Upper CI Annual Value of DALYs lost -	$866	$1,089	$945	$475	***$371***
	95% Upper CI Annual Value of DALYs lost -	$6,510	$8,987	$7,335	$2,435	***$1,194***
Buffalo, NY (Cold)	Median Annual Value of DALYs lost - Family of 4	$181	***$95***	$168	$309	$378
	68% Upper CI Annual Value of DALYs lost - Family of 4	$736	$843	$771	***$434***	$445
	95% Upper CI Annual Value of DALYs lost - Family of 4	$5,263	$6,959	$5,690	$1,453	***$994***
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs lost - Family of 4	$185	$84	$159	***$327***	$408
	68% Upper CI Annual Value of DALYs lost - Family of 4	$657	$739	$701	***$382***	$430
	95% Upper CI Annual Value of DALYs lost - Family of 4	$4,519	$6,090	$5,131	$833	***$606***
Houghton, MI (Very Cold)	Median Annual Value of DALYs lost - Family of 4	$156	***$86***	$138	$248	$306
	68% Upper CI Annual Value of DALYs lost - Family of 4	$646	$763	$702	***$325***	$333
	95% Upper CI Annual Value of DALYs lost - Family of 4	$4,644	$6,290	$5,308	$952	***$548***
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$192	***$112***	$173	$289	$345
	68% Upper CI Annual Value of DALYs lost -	$811	$1,005	$884	***$459***	$415
	95% Upper CI Annual Value of DALYs lost -	$5,868	$8,296	$6,685	$1,851	***$983***
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$156	***$107***	$130	$198	$235
	68% Upper CI Annual Value of DALYs lost -	$744	$959	$828	$363	***$302***
	95% Upper CI Annual Value of DALYs lost -	$5,546	$7,917	$6,532	$1,716	***$851***
	Cell Legend:	(shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate		***$$$*** Minimum cost for DALY risk level		

Table I.22: WC-2 Non-Cap. Cost w DALYs: DC mAER, T_{Clg}=23.4 °C

	Location (Climate Zone) T_{Clg} = 23.4 °C	Total Annual Non-Capital Monetized Cost - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$159	***$101***	$115	$198	$226
	68% Upper CI Annual Value of DALYs lost -	$783	$905	$876	$582	***$394***
	95% Upper CI Annual Value of DALYs lost -	$5,879	$7,471	$7,089	$3,718	***$1,766***
Arcata, CA (Marine)	Median Annual Value of DALYs	$164	***$86.9***	$87.3	$183	$225
	68% Upper CI Annual Value of DALYs lost -	$620	$778	$776	$567	***$393***
	95% Upper CI Annual Value of DALYs lost -	$4,344	$6,423	$6,401	$3,703	***$1,765***
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$174	***$121***	$143	$214	$240
	68% Upper CI Annual Value of DALYs lost -	$866	$1,089	$1,010	$598	***$408***
	95% Upper CI Annual Value of DALYs lost -	$6,510	$8,987	$8,085	$3,734	***$1,780***
Buffalo, NY (Cold)	Median Annual Value of DALYs	$181	***$95***	$108	$231	$280
	68% Upper CI Annual Value of DALYs lost -	$736	$843	$823	$615	***$448***
	95% Upper CI Annual Value of DALYs lost -	$5,263	$6,959	$6,664	$3,751	***$1,820***
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	$185	***$84***	$89	$223	$282
	68% Upper CI Annual Value of DALYs lost -	$657	$739	$733	$607	***$450***
	95% Upper CI Annual Value of DALYs lost -	$4,519	$6,090	$5,985	$3,743	***$1,822***
Houghton, MI (Very Cold)	Median Annual Value of DALYs	$156	***$86***	$91	$185	$222
	68% Upper CI Annual Value of DALYs lost -	$646	$763	$751	$569	***$390***
	95% Upper CI Annual Value of DALYs lost -	$4,644	$6,290	$6,141	$3,705	***$1,762***
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$192	***$112***	$130	$240	$282
	68% Upper CI Annual Value of DALYs lost -	$811	$1,005	$975	$624	***$450***
	95% Upper CI Annual Value of DALYs lost -	$5,868	$8,296	$7,874	$3,760	***$1,822***
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$156	***$107***	$118	$181	$205
	68% Upper CI Annual Value of DALYs lost -	$744	$959	$908	$565	***$373***
	95% Upper CI Annual Value of DALYs lost -	$5,546	$7,917	$7,356	$3,701	***$1,745***
	Cell Legend:	(shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate		***$$$*** Minimum cost for DALY risk level		

Table I.23: WC-2 Non-Cap. Cost Savings from DC mAER, T_{Clg}=23.4 ^oC

	Location (Climate Zone) T_{Clg} = 23.4 ^oC	Total Annual Non-Capital Monetized Savings - Demand Controlled mAER ($/y)				
		ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Amarillo, TX (Mixed-Dry)	Median Annual Value of DALYs	$0	$2	$36	$38	$54
	68% Upper CI Annual Value of DALYs lost -	$0	$14	-$65	-$180	-$34
	95% Upper CI Annual Value of DALYs lost -	$0	$112	-$888	-$1,964	-$760
Arcata, CA (Marine)	Median Annual Value of DALYs	$0	$0	$53	$76	$120
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$74	-$279	$120
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$1,113	-$3,180	$120
Austin, TX (Hot-Humid)	Median Annual Value of DALYs	$0	$0	$19	$22	$31
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$65	-$122	-$37
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$751	-$1,298	-$585
Buffalo, NY (Cold)	Median Annual Value of DALYs	$0	$0	$61	$78	$97
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$52	-$181	-$4
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$973	-$2,298	-$827
Fairbanks, AK (Sub-Arctic)	Median Annual Value of DALYs	$0	$0	$70	$103	$126
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$31	-$225	-$20
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$854	-$2,911	-$1,216
Houghton, MI (Very Cold)	Median Annual Value of DALYs	$0	$0	$47	$63	$84
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$49	-$244	-$58
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$833	-$2,753	-$1,214
Los Angeles, CA (Hot-Dry)	Median Annual Value of DALYs	$0	$0	$43	$49	$63
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$91	-$165	-$35
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$1,189	-$1,909	-$839
Knoxville, TN (Mixed-Humid)	Median Annual Value of DALYs	$0	$0	$12	$16	$31
	68% Upper CI Annual Value of DALYs lost -	$0	$0	-$80	-$202	-$70
	95% Upper CI Annual Value of DALYs lost -	$0	$0	-$824	-$1,986	-$893
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	$$$ Savings		

Table I.24: Constant mAER Thermal Energy Summary: WC-2/AU

Scenario	Annual Thermal Energy Use [(GJ/MWh$_{th}$/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Constant mAER / GPF $C_{HCHO,i,n}$ ≤ 81 ppb**			**Constant mAER /GPF $C_{HCHO,i,n}$ ≤ 40 ppb**			**Constant mAER /GPF $C_{HCHO,i,n}$ ≤ 16 ppb**			**Constant mAER / GPF $C_{HCHO,i,n}$ ≤ 7 ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
Constant mAER	76.7	21,306	72.7	102.9	28,584	97.5	114.6	31,834	108.6	147.6	41,000	139.9	262.3	72,862	248.6

Table I.25: Constant mAER: mAER and C_{HCHO} Summary: WC-2/AU

Scenario	**Base Case ASHRAE 62.2-2016 Min mAER**			**Constant mAER CHCHO,i,n ≤ 81 ppb**			**Constant mAER CHCHO,i,n ≤ 40 ppb**			**Constant mAER CHCHO,i,n ≤ 16 ppb**			**Constant mAER CHCHO,i,n ≤ 7 ppb**		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Constant mAER	0.166	45	34	0.295	34	23	0.35	29	18	0.50	15	8	1.00	2	2

Table I.26: Constant mAER: Total Energy Cost w SCC: WC-2/AU

Scenario	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
	Base Case ASHRAE 62.2-2016 Min mAER	**Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb**	**Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb**	**Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb**	**Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb**
Constant mAER	$707	$986	$1,109	$1,455	$2,644

Table I.27: Constant mAER: Non-Cap. Cost w DALYs: WC-2/AU

		Total Non-Capital Monetized Cost - Constant mAER				
	Scenario	**Base Case ASHRAE 62.2-2016 Min mAER = 0.166 h^{-1}**	**Constant mAER CO2 = 600 ppm; mAER=0.295 h^{-1}**	**mAER = 0.35 h^{-1}**	**mAER = 0.50 h^{-1}**	**mAER = 1.00 h^{-1}**
Constant mAER	Median Annual Value of DALYs lost - Family of 4	***$809***	$1,055	$1,163	$1,479	$2,650
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,625	$1,607	***$1,595***	$1,671	$2,698
	95% Upper CI Annual Value of DALYs lost - Family of 4	$8,289	$6,115	$5,123	$3,239	***$3,090***
	Cell Legend:	***$$$*** Minimum cost for DALY risk level				

Table I.28: Infiltration Factors (α) for WC-2/AU

	Infiltration Factor, α (unitless)				
Annual Average Air Exchange Rates	**Base Case ASHRAE 62.2-2016 Min mAER**	**Constant mAER CO_2 < 600 ppm**	**Constant mAER mAER = 0.35 h^{-1}**	**Constant mAER mAER = 0.5 h^{-1}**	**Constant mAER mAER = 1.0 h^{-1}**
Constant mAER, h^{-1}	0.166	0.295	0.35	0.50	1.0
λinf, h^{-1}	0.045	0.045	0.045	0.045	0.045
λ_{tot}, h^{-1}	0.166	0.295	0.35	0.50	1.0
Infiltration Factor, α, unitless	0.271	0.153	0.129	0.090	0.045

Table I.29: Exploratory Thermal Energy Summary: WC-2/AU: C/DC mAER

Scenario	Annual Thermal Energy Use [(GJ/MWh$_{th}$/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Constant mAER / GPF $C_{HCHO,i,n} \le 81$ ppb**			**Constant mAER /GPF $C_{HCHO,i,n} \le 40$ ppb**			**Constant mAER /GPF $C_{HCHO,i,n} \le 16$ ppb**			**Constant mAER / GPF $C_{HCHO,i,n} \le 7$ ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
Lower Emission Rate Base Case ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	88.8	24,667	84.2	145.8	40,500	138.2	168.3	46,750	159.5
25% Lower ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	60.8	16,889	57.6	132.7	36,861	125.8	162.4	45,111	153.9
50% Lower ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	52.6	14,611	49.9	107.1	29,750	101.5	150.8	41,889	142.9
Gas Phase Filtration $\lambda_{u,\,fan}$ [up to ASHRAE Min] + GPF	76.7	21,306	72.7	52.6	14,611	49.9	76.700	21,306	72.7	76.7	21,306	72.7	76.7	21,306	72.7
Energy Recovery Ventilator ERV-A + $\lambda_{u,\,fan} = \lambda_{inf}$	65.4	18,167	62.0	52.6	14,611	49.9	73.2	20,333	69.4	140.7	39,084	133.4	148.8	41,334	141.0
ERV-B + $\lambda_{u,\,fan} = \lambda_{inf}$	58.6	16,278	55.5	52.6	14,611	49.9	61.1	16,972	57.9	102.0	28,334	96.7	128.0	35,556	121.3

Scenario	Annual Thermal Energy Use [(GJ/MkWh$_{th}$/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**DC mAER / GPF $C_{HCHO,i,n} \le 81$ ppb**			**DC mAER / GPF $C_{HCHO,i,n} \le 40$ ppb**			**DC mAER / GPF $C_{HCHO,i,n} \le 16$ ppb**			**DC mAER / GPF $C_{HCHO,i,n} \le 7$ ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
Lower Emission Rates Base Case ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	78.4	21,778	74.3	127.0	35,278	120.4	148.7	41,306	140.9
25% Lower ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	57.7	16,028	54.7	114.6	31,834	108.6	143	39,723	135.5
50% Lower ER$_{HCHO}$	76.7	21,306	72.7	52.6	14,611	49.9	52.6	14,611	49.9	91.9	25,528	87.1	131.7	36,584	124.8
Gas Phase Filtration $\lambda_{u,\,fan}$ [up to ASHRAE Min] + GPF	76.7	21,306	72.7	52.6	14,611	49.9	76.700	21,306	72.7	76.7	21,306	72.7	76.7	21,306	72.7
Energy Recovery Ventilator ERV-A + $\lambda_{u,\,fan} = \lambda_{inf}$	65.4	18,167	62.0	52.6	14,611	49.9	64.2	17,833	60.9	93.1	25,861	88.2	129.1	35,861	122.4
ERV-B + $\lambda_{u,\,fan} = \lambda_{inf}$	58.6	16,278	55.5	52.6	14,611	49.9	56.9	15,806	53.9	81.4	22,611	77.2	100.5	27,917	95.3

Scenario	% Energy Savings of Deamnd Controlled vs. Constant mAER				
		$C_{HCHO,i,n} \le 81$ ppb	**$C_{HCHO,i,n} \le 40$ ppb**	**$C_{HCHO,i,n} \le 16$ ppb**	**$C_{HCHO,i,n} \le 7$ ppb**
			House + Ventilation	House + Ventilation	House + Ventilation
		%	%	%	%
Lower Emission Rates Base Case ER$_{HCHO}$		0%	12%	13%	12%
25% Lower ER$_{HCHO}$		0%	5%	14%	12%
50% Lower ER$_{HCHO}$		0%	0%	14%	13%
Gas Phase Filtration $\lambda_{u,\,fan}$ [up to ASHRAE Min] + GPF		0%	0%	0%	0%
Energy Recovery Ventilator ERV-A + $\lambda_{u,\,fan} = \lambda_{inf}$		0%	12%	34%	13%
ERV-B + $\lambda_{u,\,fan} = \lambda_{inf}$		0%	7%	20%	21%

[a] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.

Cell Legend: (shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate

Table I.30: Exploratory mAER and C_{HCHO} Summary: WC-2/AU: C/DC mAER

Scenario	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER CHCHO,i,n ≤ 81 ppb			Constant mAER CHCHO,i,n ≤ 40 ppb			Constant mAER CHCHO,i,n ≤ 16 ppb			Constant mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Lower Emission Rates Base Case ER_{HCHO}	0.166	45	34	0.000	60	46	0.226	40	29	0.492	16	9	0.592	7	4
25% Lower ER_{HCHO}	0.166	34	26	0.000	45	34	0.079	40	31	0.433	16	9	0.566	7	4
50% Lower ER_{HCHO}	0.166	23	17	0.000	30	23	0.001	30	23	0.315	16	10	0.514	7	4
Gas Phase Filtration $\lambda_{u,\ fan}$ [up to ASHRAE Min] + GPF	0.166	45	34	0.000	60	46	0.166	40	29	0.166	16	9	0.166	7	4
GPF	0.000			0.000			0.091			0.533			0.699		
Energy Recovery Ventilator ERV-A + $\lambda_{u,\ fan} = \lambda_{inf}$	0.166	45	31	0	60	45	0.225	40	25	0.491	16	7	0.591	7	3
ERV-B + $\lambda_{u,\ fan} = \lambda_{inf}$	0.166	45	31	0	60	45	0.225	40	25	0.491	17	7	0.591	7	3

Scenario	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER CHCHO,i,n ≤ 81 ppb			Demand Controlled mAER CHCHO,i,n ≤ 40 ppb			Demand Controlled mAER CHCHO,i,n ≤ 16 ppb			Demand Controlled mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann Avg. mAER	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Lower Emission Rates Base Case ER_{HCHO}	0.166	45	34	0.000	60	46	0.122	40	36	0.370	16	16	0.470	7	7
25% Lower ER_{HCHO}	0.166	34	26	0.000	45.0	34.0	0.030	40	33	0.311	16	16	0.444	7	7
50% Lower ER_{HCHO}	0.166	23	17	0.000	30.0	23.0	0.000	30	23	0.187	16	15	0.392	7	7
Gas Phase Filtration $\lambda_{u,\ fan}$ [up to ASHRAE Min] + GPF	0.166	45.0	34.0	0.000	60	46	0.166	40	28	0.166	16	15	0.166	7	6
GPF	0.000			0.000			0.038			0.335			0.499		
Energy Recovery Ventilator ERV-A + $\lambda_{u,\ fan} = \lambda_{inf}$	0.166	45	31	0.000	60	45	0.098	40	37	0.327	16	16	0.427	7	7
ERV-B + $\lambda_{u,\ fan} = \lambda_{inf}$	0.166	45	31	0.000	60	45	0.098	40	37	0.327	16	16	0.427	7	7
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Table I.31: Exploratory Total Energy Cost with SCC: WC-2/AU: C/DC mAER

Scenario	Total Annual Energy Cost Including Societal Cost of Capital ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ER_{HCHO}	$707	$425	$836	$1,436	$1,670
25% Lower ER_{HCHO}	$707	$425	$532	$1,299	$1,609
50% Lower ER_{HCHO}	$707	$425	$425	$1,030	$1,488
Gas Phase Filtration $\lambda_{u, fan}$ [up to ASHRAE Min] + GPF	$707	$425	$754	$987	$1,074
Energy Recovery Ventilator* ERV-A + $\lambda_{u, fan} = \lambda_{inf}$	$615	$425	$709	$1,390	$1,512
ERV-B + $\lambda_{u, fan} = \lambda_{inf}$	$560	$425	$612	$1,082	$1,344

Scenario	Total Annual Energy Cost Including Societal Cost of Capital ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ER_{HCHO}	$707	$425	$697	$1,220	$1,448
25% Lower ER_{HCHO}	$707	$425	$482	$1,089	$1,388
50% Lower ER_{HCHO}	$707	$425	$425	$840	$1,270
Gas Phase Filtration $\lambda_{u, fan}$ [up to ASHRAE Min] + GPF	$707	$425	$727	$883	$969
Energy Recovery Ventilator* ERV-A + $\lambda_{u, fan} = \lambda_{inf}$	$615	$425	$570	$924	$1,270
ERV-B + $\lambda_{u, fan} = \lambda_{inf}$	$560	$425	$511	$829	$1,036

Cell Legend: mAER < ASHRAE 62.2-2016 minimum required ventilation rate

* Includes fan energy for ventilation air through HEPA/Carbon, but not through ERV

Table I.32: Exploratory Energy Cost w SCC Savings from DC: WC-2/AU

Scenario	Total Annual Energy Savings from Demand Controlled mAER ($/y) Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ER_{HCHO}	$0	$0	$139	$216	$222
25% Lower ER_{HCHO}	$0	$0	$51	$210	$221
50% Lower ER_{HCHO}	$0	$0	$1	$190	$218
Gas Phase Filtration $\lambda_{u, fan}$ [up to ASHRAE Min] + GPF	$0	$0	$28	$104	$105
Energy Recovery Ventilator* ERV-A + $\lambda_{u, fan} = \lambda_{inf}$	$0	$0	$140	$467	$242
ERV-B + $\lambda_{u, fan} = \lambda_{inf}$	$0	$0	$101	$253	$308

Cell Legend: mAER < ASHRAE 62.2-2016 minimum required ventilation rate

* Includes fan energy for ventilation air through HEPA/Carbon, but not through ERV

Table I.33: Energy Savings with C mAER vs. Base Case with C mAER

Scenario	Annual Value of Energy Savings using Scenario with Constant mAER vs. Base Case with Constant mAER ($/y) Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ER_{HCHO}	$0	$0	$0	$0	$0
25% Lower ER_{HCHO}	$0	$0	$303	$137	$61
50% Lower ER_{HCHO}	$0	$0	$411	$406	$182
Gas Phase Filtration $\lambda_{u, fan}$ [up to ASHRAE Min] + GPF	$0	$0	$81	$449	$596
Energy Recovery Ventilator* ERV-A + $\lambda_{u, fan} = \lambda_{inf}$	$91	$0	$126	$46	$158
ERV-B + $\lambda_{u, fan} = \lambda_{inf}$	$146	$0	$224	$354	$326

Filled cells mAER is less than ASHRAE 62.2-2016 minimum required ventilation rate

* Includes fan energy for ventilation air through HEPA/Carbon, but not through ERV

Table I.34: Exploratory Non-Cap. Cost w DALYs: WC-2/AU – C mAER

		Total Non-Capital Monetized Cost - Constant mAER ($/y)				
	Scenario	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n} \le 81$ ppb	Constant mAER $C_{HCHO,i,n} \le 40$ ppb	Constant mAER $C_{HCHO,i,n} \le 16$ ppb	Constant mAER $C_{HCHO,i,n} \le 7$ ppb
Lower Emission Rate Base Case ER_{HCHO}	Median Annual Value of DALYs lost - Family of 4	$809	***$563***	$923	$1,463	$1,682
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,625	$1,667	***$1,619***	$1,679	$1,778
	95% Upper CI Annual Value of DALYs lost - Family of 4	$8,289	$10,683	$7,303	$3,443	***$2,562***
25% Lower ER_{HCHO}	Median Annual Value of DALYs lost - Family of 4	$785	***$527***	$625	$1,326	$1,621
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,409	***$1,343***	$1,369	$1,542	$1,717
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,505	$8,007	$7,445	$3,306	***$2,501***
50% Lower ER_{HCHO}	Median Annual Value of DALYs lost - Family of 4	$758	***$494***	$494	$1,060	$1,500
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,166	***$1,046***	***$1,046***	$1,300	$1,596
	95% Upper CI Annual Value of DALYs lost - Family of 4	$4,498	$5,554	$5,554	$3,260	***$2,380***
Gas Phase Filtration λu, fan [up to ASHRAE Min] + GPF	Median Annual Value of DALYs lost - Family of 4	$809	***$563***	$841	$1,014	$1,086
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,625	$1,667	$1,537	$1,230	***$1,182***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$8,289	$10,683	$7,221	$2,994	***$1,966***
Energy Recovery Ventilator* ERV-A + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$708	***$560***	$784	$1,415	$1,521
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,452	$1,640	***$1,384***	$1,583	$1,593
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,528	$10,460	$6,284	$2,955	***$2,181***
ERV-B + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$653	***$560***	$687	$1,103	$1,353
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,397	$1,640	$1,287	***$1,271***	$1,425
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,473	$10,460	$6,187	$2,643	***$2,013***
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$***	Minimum cost for DALY risk level	
	* Includes fan energy for ventilation air through HEPA/Carbon filter, but not through ERV					

Table I.35: Exploratory Non-Cap. Cost w DALYs: WC-2/AU – DC mAER

	Scenario	Total Non-Capital Monetized Cost - Demand Controlled mAER ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ERHCHO	Median Annual Value of DALYs lost - Family of 4	$809	***$563***	$805	$1,268	$1,469
	68% Upper CI Annual Value of DALYs lost - Family of 4	*$1,625*	$1,667	$1,669	$1,652	$1,637
	95% Upper CI Annual Value of DALYs lost - Family of 4	$8,289	$10,683	$8,725	$4,788	***$3,009***
25% Lower ERHCHO	Median Annual Value of DALYs lost - Family of 4	$785	***$527***	$581	$1,137	$1,409
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,409	***$1,343***	$1,373	$1,521	$1,577
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,505	$8,007	$7,841	$4,657	***$2,949***
50% Lower ERHCHO	Median Annual Value of DALYs lost - Family of 4	$758	***$494***	***$494***	$885	$1,291
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,166	***$1,046***	***$1,046***	$1,245	$1,459
	95% Upper CI Annual Value of DALYs lost - Family of 4	$4,498	$5,554	$5,554	$4,185	***$2,831***
Gas Phase Filtration λu, fan [up to ASHRAE Min] + GPF	Median Annual Value of DALYs lost - Family of 4	$809	***$563***	$811	$928	$987
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,625	$1,667	$1,483	$1,288	***$1,131***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$8,289	$10,683	$6,971	$4,228	***$2,307***
Energy Recovery Ventilator* ERV-A + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$708	***$560***	$681	$972	$1,288
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,452	$1,640	$1,569	$1,356	***$1,456***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,528	$10,460	$8,821	$4,492	***$2,828***
ERV-B + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$653	***$560***	$622	$877	$1,057
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,397	$1,640	$1,510	$1,261	***$1,225***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,473	$10,460	$8,762	$4,397	***$2,597***

Cell Legend: [shaded] mAER < ASHRAE 62.2-2016 minimum required ventilation rate; ***$$$*** Minimum cost for DALY risk level

* Includes fan energy for ventilation air through HEPA/Carbon filter, but not through ERV

Table I.36: Exploratory Non-Cap. Cost Savings from DC: WC-2/AU

	Scenario	Total Non-Capital Monetized Cost Savings from Demand Controlled mAER ($/y) Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Lower Emission Rate Base Case ERHCHO	Median Annual Value of DALYs lost - Family of 4	$0	$0	$118	$195	$213
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$50	$27	$141
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$1,422	-$1,345	-$447
25% Lower ERHCHO	Median Annual Value of DALYs lost - Family of 4	$0	$0	$45	$189	$212
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$3	$21	$140
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$395	-$1,351	-$448
50% Lower ERHCHO	Median Annual Value of DALYs lost - Family of 4	$0	$0	$1	$175	$209
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	$1	$55	$137
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	$1	-$925	-$451
Gas Phase Filtration λu, fan [up to ASHRAE Min] + GPF	Median Annual Value of DALYs lost - Family of 4	$0	$0	$31	$86	$99
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	<u>$55</u>	-$58	<u>$51</u>
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	$251	-$1,234	-$341
Energy Recovery Ventilator* ERV-A + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$0	$0	$104	$444	$233
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$184	$228	$137
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$2,536	-$1,536	-$647
ERV-B + λu, fan = λinf	Median Annual Value of DALYs lost - Family of 4	$0	$0	$65	$226	$296
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$223	$10	$200
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$2,575	-$1,754	-$584

Cell Legend: [shaded] mAER < ASHRAE 62.2-2016 minimum required ventilation rate; <u>$$$</u> Savings

* Includes fan energy for ventilation air through HEPA/Carbon filter, but not through ERV

Table I.37: Thermal Energy Summary: WC-2/LA $C_{HCHO,\ out}$; C/DC mAER

Location (Climate Zone)	Annual Energy Use [(GJ/kWh$_{th}$/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb**			**Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
Los Angeles $C_{HCHO,o}$ = 5 ppb	32.1	8,917	30.4	27.5	7,639	26.1	35.6	9,889	33.7	60.9	16,917	57.7	72.9	20,250	69.1
Los Angeles $C_{HCHO,o}$ = 10 ppb	32.1	8,917	30.4	27.5	7,639	26.1	37.0	10,278	35.1	63.5	17,639	60.2	75.6	21,000	71.7
Los Angeles $C_{HCHO,o}$ = 15 ppb	32.1	8,917	30.4	27.5	7,639	26.1	38.7	10,750	36.7	66.1	18,361	62.7	78.3	21,750	74.2

Location (Climate Zone)	Annual Energy Use [(GJ/kWh$_{th}$/MBTU[a])/y]														
	Base Case ASHRAE 62.2-2016 Min mAER			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb**			**Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
Los Angeles $C_{HCHO,o}$ = 5 ppb	32.1	8,917	30.4	27.5	7,639	26.1	28.9	8,028	27.4	40.2	11,167	38.1	50.7	14,083	48.1
Los Angeles $C_{HCHO,o}$ = 10 ppb	32.1	8,917	30.4	27.5	7,639	26.1	29.0	8,056	27.5	42.5	11,806	40.3	53.2	14,778	50.4
Los Angeles $C_{HCHO,o}$ = 15 ppb	32.1	8,917	30.4	27.5	7,639	26.1	29.1	8,083	27.6	44.7	12,417	42.4	55.7	15,472	52.8

Location (Climate Zone) T_{Clg} = 24.4 °C	% Energy Savings of Deamnd Controlled vs. Constant mAER						
					House + Venitilation	House + Venitilation	House + Venitilation
				%	%	%	%
Los Angeles $C_{HCHO,o}$ = 5 ppb				0%	19%	34%	30%
Los Angeles $C_{HCHO,o}$ = 10 ppb				0%	22%	33%	30%
Los Angeles $C_{HCHO,o}$ = 15 ppb				0%	25%	32%	29%
Average All Zones				0%	22%	33%	30%

[a] MBTU as used in this dissertation respresents a mega or 1,000,000 BTU.

Cell Legend: (shaded) mAER < ASHRAE 62.2-2016 minimum required ventilation rate

Table I.38: mAER and $C_{HCHO, in}$ Summary: WC-2/LA $C_{HCHO, out}$; C/DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Base Case ASHRAE 62.2-2016 Min mAER			Constant mAER CHCHO,i,n ≤ 81 ppb			Constant mAER CHCHO,i,n ≤ 40 ppb			Constant mAER CHCHO,i,n ≤ 16 ppb			Constant mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Los Angeles $C_{HCHO,o}$ = 5 ppb	0.165	45	29	0.000	59	40	0.226	59	40	0.492	16	5	0.591	7	3
Los Angeles $C_{HCHO,o}$ = 10 ppb	0.165	47	31	0.000	61	42	0.248	40	23	0.514	16	6	0.613	7	4
Los Angeles $C_{HCHO,o}$ = 15 ppb	0.165	49	33	0.000	63	44	0.270	40	23	0.536	16	8	0.636	6	6
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Location (Climate Zone) T_{Clg} = 24.4 °C	Base Case ASHRAE 62.2-2016 Min mAER			Demand Controlled mAER CHCHO,i,n ≤ 81 ppb			Demand Controlled mAER CHCHO,i,n ≤ 40 ppb			Demand Controlled mAER CHCHO,i,n ≤ 16 ppb			Demand Controlled mAER CHCHO,i,n ≤ 7 ppb		
	mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann. Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb	Ann Avg. mAER h^{-1}	Max $C_{HCHO,i}$ ppb	Ann. Avg. $C_{HCHO,i}$ ppb
Los Angeles $C_{HCHO,o}$ = 5 ppb	0.165	45	29	0.000	59	40	0.065	40	36	0.313	16	16	0.411	7	7
Los Angeles $C_{HCHO,o}$ = 10 ppb	0.165	47	31	0.000	61	42	0.078	40	37	0.331	16	16	0.430	7	7
Los Angeles $C_{HCHO,o}$ = 15 ppb	0.165	49	33	0.000	63	44	0.091	40	38	0.353	16	16	0.452	7	7
Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate													

Table I.39: Total Energy Cost w SCC: WC-2/LA $C_{HCHO, out}$; C/DC mAER

	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
Scenario	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Constant mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Los Angeles $C_{HCHOC,o}$ = 5 ppb	$453	$291	$532	$984	$1,179
Los Angeles $C_{HCHOC,o}$ = 10 ppb	$453	$291	$562	$1,026	$1,223
Los Angeles $C_{HCHOC,o}$ = 15 ppb	$453	$291	$596	$1,069	$1,267

	Total Annual Energy Cost Including Societal Cost of Capital ($/y)				
Scenario	Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 81 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 40 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 16 ppb	Demand Controlled mAER $C_{HCHO,i,n}$ ≤ 7 ppb
Los Angeles $C_{HCHOC,o}$ = 5 ppb	$453	$291	$351	$641	$820
Los Angeles $C_{HCHOC,o}$ = 10 ppb	$453	$291	$361	$678	$859
Los Angeles $C_{HCHOC,o}$ = 15 ppb	$453	$291	$371	$716	$901
Cell Legend:	mAER < ASHRAE 62.2-2016 minimum required ventilation rate				

Table I.40: Energy Cost w SCC Savings from DC: WC-2/LA $C_{HCHO, out}$

	Total Annual Energy Savings from Demand Controlled mAER ($/y)				
Scenario	Base Case ASHRAE 62.2-2016 Min mAER	$C_{HCHO,i,n}$ ≤ 81 ppb	$C_{HCHO,i,n}$ ≤ 40 ppb	$C_{HCHO,i,n}$ ≤ 16 ppb	$C_{HCHO,i,n}$ ≤ 7 ppb
Los Angeles $C_{HCHOC,o}$ = 5 ppb	$0	$0	$182	$342	$359
Los Angeles $C_{HCHOC,o}$ = 10 ppb	$0	$0	$202	$348	$363
Los Angeles $C_{HCHOC,o}$ = 15 ppb	$0	$0	$225	$353	$366
Cell Legend:	mAER < ASHRAE 62.2-2016 minimum required ventilation rate				

Table I.41: Total Non-Cap. Cost w DALYs: WC-2/LA $C_{HCHO,out}$ C mAER

		Total Non-Capital Monetized Cost - Constant mAER				
	DALY Statistic	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER CHCHO,i,n ≤ 81 ppb	Constant mAER CHCHO,i,n ≤ 40 ppb	Constant mAER CHCHO,i,n ≤ 16 ppb	Constant mAER CHCHO,i,n ≤ 7 ppb
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 5 ppb	Median Annual Value of DALYs lost - Family of 4	$564	***$431***	$678	$1,043	$1,240
	68% Upper CI Annual Value of DALYs lost - Family of 4	***$1,260***	$1,391	$1,638	$1,163	$1,312
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,944	$9,231	$9,478	$2,143	***$1,900***
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 10 ppb	Median Annual Value of DALYs lost - Family of 4	$570	***$437***	$658	$1,090	$1,289
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,314	$1,445	***$1,210***	$1,234	$1,385
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,390	$9,677	$5,718	$2,410	***$2,169***
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 15 ppb	Median Annual Value of DALYs lost - Family of 4	$576	***$443***	$693	$1,141	$1,341
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,368	$1,499	***$1,245***	$1,333	$1,485
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,836	$10,123	$5,753	$2,901	***$2,661***
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$*** Minimum cost for DALY risk level		

Table I.42: Total Non-Cap. Cost w DALYs: WC-2/LA $C_{HCHO,out}$ DC mAER

		Total Non-Capital Monetized Cost - Demand Controlled mAER				
	DALY Statistic	Base Case ASHRAE 62.2-2016 Min mAER	Demand Controlled mAER CHCHO,i,n ≤ 81 ppb	Demand Controlled mAER CHCHO,i,n ≤ 40 ppb	Demand Controlled mAER CHCHO,i,n ≤ 16 ppb	Demand Controlled mAER CHCHO,i,n ≤ 7 ppb
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 5 ppb	Median Annual Value of DALYs lost - Family of 4	$564	***$431***	$479	$718	$877
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,260	$1,391	$1,343	$1,102	***$1,045***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$6,944	$9,231	$8,399	$4,238	***$2,417***
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 10 ppb	Median Annual Value of DALYs lost - Family of 4	$570	***$437***	$493	$757	$919
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,314	$1,445	$1,381	$1,141	**$1,087**
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,390	$9,677	$8,633	$4,277	**$2,459**
Los Angeles, CA (Hot-Dry) $C_{HCHO,o}$ = 15 ppb	Median Annual Value of DALYs lost - Family of 4	$576	***$443***	$506	$797	$962
	68% Upper CI Annual Value of DALYs lost - Family of 4	$1,368	$1,499	$1,418	$1,181	***$1,130***
	95% Upper CI Annual Value of DALYs lost - Family of 4	$7,836	$10,123	$8,866	$4,317	***$2,502***
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	***$$$*** Minimum cost for DALY risk level		

Table I.43: Total Non-Cap. Cost Savings from DC mAER: WC-2/LA $C_{HCHO,out}$

		Total Non-Capital Monetized Savings from Demand Controlled mAER ($)				
	DALY Statistic	Base Case ASHRAE 62.2-2016 Min mAER	Constant mAER $C_{HCHO,i,n} \leq 81$ ppb	Constant mAER $CH_{CHO,i,n} \leq 40$ ppb	Constant mAER $C_{HCHO,i,n} \leq 16$ ppb	Constant mAER $C_{HCHO,i,n} \leq 7$ ppb
Los Angeles, CA (Hot-Dry) $C_{HCHO,o} = 5$ ppb	Median Annual Value of DALYs lost - Family of 4	$0	$0	$199	$324	$363
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	$295	$60	$267
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	$1,079	-$2,096	-$517
Los Angeles, CA (Hot-Dry) $C_{HCHO,o} = 10$ ppb	Median Annual Value of DALYs lost - Family of 4	$0	$0	$166	$334	$370
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$170	$94	$298
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$2,914	-$1,866	-$290
Los Angeles, CA (Hot-Dry) $C_{HCHO,o} = 15$ ppb	Median Annual Value of DALYs lost - Family of 4	$0	$0	$187	$344	$379
	68% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$173	$152	$355
	95% Upper CI Annual Value of DALYs lost - Family of 4	$0	$0	-$3,113	-$1,416	$159
	Cell Legend:		mAER < ASHRAE 62.2-2016 minimum required ventilation rate	$$$ Savings		

Table I.44: Superposition Summary: WC-2/AU

Location (Climate Zone)	Annual Energy Use [(GJ/kWh$_{th}$/MBTU^{a})/y]														
	Base Case ASHRAE 62.2-2016 Min mAER = 0.166 h^{-1}			**Constant mAER = 0.295 h^{-1} CO2 < 600 ppm**			**Constant mAER =0.35 h^{-1}**			**Constant mAER =0.50 h^{-1}**			**Constant mAER = 1.00 h^{-1}**		
	House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation			House + Venitilation		
	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y	GJ/y	kWh$_{th}$/y	MBTU/y
RMS Superposition															
Austin, TX (Hot-Humid)	76.7	21,306	72.7	102.9	28,584	97.5	114.6	31,834	108.6	147.6	41,000	139.9	262.3	72,862	248.6
Ann. Avg. $C_{HCHO,I}$ (ppb)	34			22.8			17.7			8.4			2		
Ann. Avg. λ_{tot} (h^{-1})	0.177			0.300			0.356			0.505			1.002		
Improved Superposition															
Austin, TX (Hot-Humid)	77.5	21,528	73.5	103.5	28,750	98.1	115.1	31,972	109.1	148.1	41,139	140.4	262.5	72,917	248.8
Ann. Avg. $C_{HCHO,i}$	33.7			22.6			17.6			8.4			2		
Ann. Avg. λ_{tot} (h^{-1})	0.177			0.300			0.356			0.505			1.002		
Annual Avg. Infiltration Fraction $\alpha = \lambda_{inf} / \lambda_{tot}$	0.25			0.15			0.13			0.09			0.05		
Difference (Improved - RMS) Superposition															
Annual Energy Use	0.8	222	0.8	0.6	167	0.6	0.5	139	0.5	0.5	139	0.5	0.2	56	0.2
Ann. Avg. $C_{HCHO,I}$ (ppb)	-0.3			-0.2			-0.1			0.0			0.0		
Ann. Avg. λ_{tot} (h^{-1})	0.0			0.0			0.0			0.0			0.0		
% Difference (Improved - RMS) Superposition															
Annual Energy Use	1.0%			0.6%			0.4%			0.3%			0.1%		
Ann. Avg. $C_{HCHO,I}$ (ppb)	-0.9%			-0.9%			-0.6%			0.0%			0.0%		
Ann. Avg. λ_{tot} (h^{-1})	0.0%			0.0%			0.0%			0.0%			0.0%		

% Difference of Root Mean Square and Improved Superposition in House WC-2 in Austin is 15 or less which is below the accuracy of the FREE model.

Table I.45: Ann. Avg. HCHO ER and Max/Min Hourly ER – WC-2, T_{Clg}=24.4 ^oC

Location (Climate Zone) T_{Clg} = 24.4 ^oC	**Annual Average HCHO Emission Rate µg/(h m^2)**	**Minimum Hourly HCHO Emission Rate µg/(h m^2)**	**Maximum Hourly HCHO Emission Rate µg/(h m^2)**	**Turner et al. Emission Rate Category***
Amarillo, TX (Mixed-Dry)	21.1	9.2	38.9	Med
Arcata, CA (Marine)	14.7	13.3	31.6	Low
Austin, TX (Hot-Humid)	25.8	12.8	39.3	Med
Buffalo, NY (Cold)	18.1	5.6	39.6	Med
Fairbanks, AK (Sub -Artic)	15.8	12.4	34.1	Med
Houghton, MI (Very Cold)	16.9	3.2	16.9	Low
Los Angeles, CA (Hot-Dry)	21.5	9.5	36.9	Med
Knoxville, TN (Mixed-Humid)	21.8	13.1	36.9	Med

*Low (9.7); Med (30.3); High (88.2) µg/(h m^2)

Table I.46: Ann. Avg. HCHO ER and Max/Min Hourly ER – WC-2, T_{Clg}=23.4 ^{o}C

Location (Climate Zone) T_{Clg} = 23.4 ^{o}C	Annual Average HCHO Emission Rate µg/(h m^2)	Minimum Hourly HCHO Emission Rate µg/(h m^2)	Maximum Hourly HCHO Emission Rate µg/(h m^2)	Turner et al. Emission Rate Category*
Amarillo, TX (Mixed-Dry)	18.7	9.2	29.7	Low
Arcata, CA (Marine)	14.6	13.3	27.5	Low
Austin, TX (Hot-Humid)	21.8	12.7	30.0	Low
Buffalo, NY (Cold)	16.8	5.6	30.2	Low
Fairbanks, AK (Sub -Artic)	15.2	12.4	26.9	Low
Houghton, MI (Very Cold)	16.0	12.3	28.2	Low
Los Angeles, CA (Hot-Dry)	19.3	9.5	29.4	Low
Knoxville, TN (Mixed-Humid)	19.2	13.1	29.3	Low

* Low (9.7); Med (30.3); High (88.2) µg/(h m^2)

Table I.47: Ann. Avg. HCHO ER and Max/Min Hourly ER – WC-3, T_{Clg}=24.4 ^oC

Location (Climate Zone) T_{Clg} = 24.4 ^oC	Annual Average HCHO Emission Rate µg/(h m^2)	Minimum Hourly HCHO Emission Rate µg/(h m^2)	Maximum Hourly HCHO Emission Rate µg/(h m^2)	Turner et al. Emission Rate Category*
Amarillo, TX (Mixed-Dry)	76.2	1.5	175.8	High
Arcata, CA (Marine)	56.9	1.5	131.1	Med
Austin, TX (Hot-Humid)	106.5	1.5	175.8	High
Buffalo, NY (Cold)	56.3	1.5	175.8	Med
Fairbanks, AK (Sub -Artic)	37.7	1.5	175.6	Med
Houghton, MI (Very Cold)	46.4	1.5	175.8	Med
Los Angeles, CA (Hot-Dry)	91.5	1.5	175.2	High
Knoxville, TN (Mixed-Humid)	80.4	1.5	175.8	High

* Low (9.7); Med (30.3); High (88.2) µg/(h m^2)

Table I.48: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, ASHRAE Base Case, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e /y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	20,889	4.3	4,858	0.051	1,608,336	553	5,411	10%
Arcata, CA (Marine)	13,722	4.1	3,347	0.055	1,734,480	596	3,943	15%
Austin, TX (Hot-Humid)	21,306	4.7	4,533	0.059	1,860,624	639	5,173	12%
Buffalo, NY (Cold)	26,278	4.2	6,257	0.052	1,639,872	564	6,820	8%
Fairbanks, AK (Sub -Artic)	45,695	4.1	11,145	0.051	1,608,336	553	11,698	5%
Houghton, MI (Very Cold)	33,028	4.1	8,056	0.052	1,639,872	564	8,619	7%
Los Angeles, CA (Hot-Dry)	8,917	4.4	2,027	0.059	1,860,624	639	2,666	24%
Knoxville, TN (Mixed-Humid)	22,389	4.4	5,088	0.058	1,829,088	629	5,717	11%
[1] Values from Table I.1							Avg. over all sites:	12%
[2] Values from Table H.6					Avg.	592		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ (value / %)	36	6%	

Table I.49: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 81 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	17,611	4.3	4,096	0.000	0	0	4,096	0%
Arcata, CA (Marine)	10,667	4.1	2,602	0.000	0	0	2,602	0%
Austin, TX (Hot-Humid)	14,611	4.7	3,109	0.000	0	0	3,109	0%
Buffalo, NY (Cold)	22,417	4.2	5,337	0.000	0	0	5,337	0%
Fairbanks, AK (Sub -Artic)	39,584	4.1	9,655	0.000	0	0	9,655	0%
Houghton, MI (Very Cold)	28,167	4.1	6,870	0.000	0	0	6,870	0%
Los Angeles, CA (Hot-Dry)	7,639	4.4	1,736	0.000	0	0	1,736	0%
Knoxville, TN (Mixed-Humid)	16,917	4.4	3,845	0.000	0	0	3,845	0%
[1] Values from Table I.1							Avg. over all sites:	0%
[2] Values from Table H.6					Avg.	0		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	0	N/A	

Table I.50: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 40 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e /y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	24,028	4.3	5,588	0.080	2,522,880	867	6,455	13%
Arcata, CA (Marine)	15,111	4.1	3,686	0.070	2,207,520	759	4,444	17%
Austin, TX (Hot-Humid)	24,667	4.7	5,248	0.080	2,522,880	867	6,115	14%
Buffalo, NY (Cold)	29,917	4.2	7,123	0.080	2,522,880	867	7,990	11%
Fairbanks, AK (Sub -Artic)	50,612	4.1	12,344	0.074	2,333,664	802	13,146	6%
Houghton, MI (Very Cold)	36,584	4.1	8,923	0.074	2,333,664	802	9,725	8%
Los Angeles, CA (Hot-Dry)	9,889	4.4	2,248	0.080	2,522,880	867	3,114	28%
Knoxville, TN (Mixed-Humid)	24,750	4.4	5,625	0.076	2,396,736	824	6,449	13%
[1] Values from Table I.1							Avg. over all sites:	14%
[2] Values from Table H.6					Avg.	832		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	39	5%	

Table I.51: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 16 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e /y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	36,195	4.3	8,417	0.175	5,518,800	1,896	10,314	18%
Arcata, CA (Marine)	26,000	4.1	6,341	0.165	5,203,440	1,788	8,130	22%
Austin, TX (Hot-Humid)	40,500	4.7	8,617	0.175	5,518,800	1,896	10,514	18%
Buffalo, NY (Cold)	44,695	4.2	10,642	0.175	5,518,800	1,896	12,538	15%
Fairbanks, AK (Sub -Artic)	74,862	4.1	18,259	0.168	5,298,048	1,821	20,080	9%
Houghton, MI (Very Cold)	54,556	4.1	13,306	0.168	5,298,048	1,821	15,127	12%
Los Angeles, CA (Hot-Dry)	16,917	4.4	3,845	0.175	5,518,800	1,896	5,741	33%
Knoxville, TN (Mixed-Humid)	39,084	4.4	8,883	0.170	5,361,120	1,842	10,725	17%
[1] Values from Table I.1							Avg. over all sites:	18%
[2] Values from Table H.6					Avg.	1,857		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	42	2%	

Table I.52: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 7 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} **= 24.4 °C**	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	41,111	4.3	9,561	0.210	6,622,560	2,276	11,836	19%
Arcata, CA (Marine)	30,472	4.1	7,432	0.200	6,307,200	2,167	9,600	23%
Austin, TX (Hot-Humid)	46,750	4.7	9,947	0.210	6,622,560	2,276	12,223	19%
Buffalo, NY (Cold)	50,667	4.2	12,064	0.210	6,622,560	2,276	14,339	16%
Fairbanks, AK (Sub -Artic)	84,501	4.1	20,610	0.204	6,433,344	2,211	22,821	10%
Houghton, MI (Very Cold)	61,778	4.1	15,068	0.204	6,433,344	2,211	17,279	13%
Los Angeles, CA (Hot-Dry)	20,250	4.4	4,602	0.210	6,622,560	2,276	6,878	33%
Knoxville, TN (Mixed-Humid)	44,861	4.4	10,196	0.205	6,464,880	2,222	12,417	18%
[1] Values from Table I.1						Avg. over all sites:		19%
[2] Values from Table H.6					Avg.	2,239		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	39	2%	

Table I.53: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 81 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e /y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	17,611	4.3	4,096	0.000	0	0	4,096	0%
Arcata, CA (Marine)	10,667	4.1	2,602	0.000	0	0	2,602	0%
Austin, TX (Hot-Humid)	14,611	4.7	3,109	0.000	0	0	3,109	0%
Buffalo, NY (Cold)	22,417	4.2	5,337	0.000	0	0	5,337	0%
Fairbanks, AK (Sub -Artic)	39,584	4.1	9,655	0.000	0	0	9,655	0%
Houghton, MI (Very Cold)	28,167	4.1	6,870	0.000	0	0	6,870	0%
Los Angeles, CA (Hot-Dry)	7,639	4.4	1,736	0.000	0	0	1,736	0%
Knoxville, TN (Mixed-Humid)	16,917	4.4	3,845	0.000	0	0	3,845	0%
[1] Values from Table I.1						Avg. over all sites:		0%
[2] Values from Table H.6					Avg.	0		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	0	N/A	

Table I.54: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 40 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	19,472	4.3	4,528	0.026	819,936	282	4,810	6%
Arcata, CA (Marine)	10,667	4.1	2,602	0.001	31,536	11	2,613	0%
Austin, TX (Hot-Humid)	21,778	4.7	4,634	0.043	1,356,048	466	5,100	9%
Buffalo, NY (Cold)	23,222	4.2	5,529	0.016	504,576	173	5,702	3%
Fairbanks, AK (Sub -Artic)	39,500	4.1	9,634	0.006	189,216	65	9,699	1%
Houghton, MI (Very Cold)	28,584	4.1	6,972	0.009	283,824	98	7,069	1%
Los Angeles, CA (Hot-Dry)	8,028	4.4	1,825	0.023	725,328	249	2,074	12%
Knoxville, TN (Mixed-Humid)	20,278	4.4	4,609	0.027	851,472	293	4,901	6%
[1] Values from Table I.1							Avg. over all sites:	5%
[2] Values from Table H.6					Avg.	205		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	139	68%	

Table I.55: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 16 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	26,772	4.3	6,226	0.108	3,405,888	1,170	7,396	16%
Arcata, CA (Marine)	14,667	4.1	3,577	0.070	2,207,520	759	4,336	17%
Austin, TX (Hot-Humid)	35,278	4.7	7,506	0.131	4,131,216	1,420	8,926	16%
Buffalo, NY (Cold)	30,167	4.2	7,183	0.093	2,932,848	1,008	8,190	12%
Fairbanks, AK (Sub -Artic)	47,889	4.1	11,680	0.075	2,365,200	813	12,493	7%
Houghton, MI (Very Cold)	35,750	4.1	8,720	0.080	2,522,880	867	9,586	9%
Los Angeles, CA (Hot-Dry)	11,167	4.4	2,538	0.110	3,468,960	1,192	3,730	32%
Knoxville, TN (Mixed-Humid)	29,556	4.4	6,717	0.107	3,374,352	1,160	7,877	15%
[1] Values from Table I.1						Avg. over all sites:		15%
[2] Values from Table H.6					Avg.	1,048		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	212	20%	

Table I.56: Ventilation Fan Energy as a Percent of Total Energy – Ventilation through HEPA/Carbon filter, C_{HCHO} ≤ 7 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	31,306	4.3	7,280	0.144	4,541,184	1,561	8,841	18%
Arcata, CA (Marine)	18,556	4.1	4,526	0.105	3,311,280	1,138	5,664	20%
Austin, TX (Hot-Humid)	41,306	4.7	8,789	0.167	5,266,512	1,810	10,598	17%
Buffalo, NY (Cold)	35,639	4.2	8,485	0.129	4,068,144	1,398	9,883	14%
Fairbanks, AK (Sub -Artic)	56,500	4.1	13,780	0.110	3,468,960	1,192	14,973	8%
Houghton, MI (Very Cold)	42,334	4.1	10,325	0.116	3,658,176	1,257	11,582	11%
Los Angeles, CA (Hot-Dry)	14,083	4.4	3,201	0.145	4,572,720	1,571	4,772	33%
Knoxville, TN (Mixed-Humid)	34,973	4.4	7,948	0.143	4,509,648	1,550	9,498	16%
[1] Values from Table I.1							Avg. over all sites:	17%
[2] Values from Table H.6					Avg.	1,435		
[3] Fan efficacy for HEPA/Carbon filter = 2910 m^3/kWh					σ / σ mean	215	15%	

Table I.57: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, ASHRAE Base Case, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	20,889	4.3	4,858	0.051	1,608,336	335	7%
Arcata, CA (Marine)	13,722	4.1	3,347	0.055	1,734,480	361	11%
Austin, TX (Hot-Humid)	21,306	4.7	4,533	0.059	1,860,624	388	9%
Buffalo, NY (Cold)	26,278	4.2	6,257	0.052	1,639,872	342	5%
Fairbanks, AK (Sub -Artic)	45,695	4.1	11,145	0.051	1,608,336	335	3%
Houghton, MI (Very Cold)	33,028	4.1	8,056	0.052	1,639,872	342	4%
Los Angeles, CA (Hot-Dry)	8,917	4.4	2,027	0.059	1,860,624	388	19%
Knoxville, TN (Mixed-Humid)	22,389	4.4	5,088	0.058	1,829,088	381	7%
[1] Values from Table I.1							8%
[2] Values from Table H.6					Avg.	359	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	22	6%

Table I.58: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 81 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	17,611	4.3	4,096	0.000	0	0	0%
Arcata, CA (Marine)	10,667	4.1	2,602	0.000	0	0	0%
Austin, TX (Hot-Humid)	14,611	4.7	3,109	0.000	0	0	0%
Buffalo, NY (Cold)	22,417	4.2	5,337	0.000	0	0	0%
Fairbanks, AK (Sub -Artic)	39,584	4.1	9,655	0.000	0	0	0%
Houghton, MI (Very Cold)	28,167	4.1	6,870	0.000	0	0	0%
Los Angeles, CA (Hot-Dry)	7,639	4.4	1,736	0.000	0	0	0%
Knoxville, TN (Mixed-Humid)	16,917	4.4	3,845	0.000	0	0	0%
[1] Values from Table I.1							0%
[2] Values from Table H.6					Avg.	0	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	0	N/A

Table I.59: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 40 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	24,028	4.3	5,588	0.080	2,522,880	526	9%
Arcata, CA (Marine)	15,111	4.1	3,686	0.070	2,207,520	460	12%
Austin, TX (Hot-Humid)	24,667	4.7	5,248	0.080	2,522,880	526	10%
Buffalo, NY (Cold)	29,917	4.2	7,123	0.080	2,522,880	526	7%
Fairbanks, AK (Sub -Artic)	50,612	4.1	12,344	0.074	2,333,664	486	4%
Houghton, MI (Very Cold)	36,584	4.1	8,923	0.074	2,333,664	486	5%
Los Angeles, CA (Hot-Dry)	9,889	4.4	2,248	0.080	2,522,880	526	23%
Knoxville, TN (Mixed-Humid)	24,750	4.4	5,625	0.076	2,396,736	499	9%
[1] Values from Table I.1							10%
[2] Values from Table H.6					Avg.	504	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	24	5%

Table I.60: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 16 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	36,195	4.3	8,417	0.175	5,518,800	1,150	14%
Arcata, CA (Marine)	26,000	4.1	6,341	0.165	5,203,440	1,084	17%
Austin, TX (Hot-Humid)	40,500	4.7	8,617	0.175	5,518,800	1,150	13%
Buffalo, NY (Cold)	44,695	4.2	10,642	0.175	5,518,800	1,150	11%
Fairbanks, AK (Sub -Artic)	74,862	4.1	18,259	0.168	5,298,048	1,104	6%
Houghton, MI (Very Cold)	54,556	4.1	13,306	0.168	5,298,048	1,104	8%
Los Angeles, CA (Hot-Dry)	16,917	4.4	3,845	0.175	5,518,800	1,150	30%
Knoxville, TN (Mixed-Humid)	39,084	4.4	8,883	0.170	5,361,120	1,117	13%
[1] Values from Table I.1							14%
[2] Values from Table H.6					Avg.	1,126	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	25	2%

Table I.61: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 7 ppb, WC-2, C mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	41,111	4.3	9,561	0.210	6,622,560	1,380	14%
Arcata, CA (Marine)	30,472	4.1	7,432	0.200	6,307,200	1,314	18%
Austin, TX (Hot-Humid)	46,750	4.7	9,947	0.210	6,622,560	1,380	14%
Buffalo, NY (Cold)	50,667	4.2	12,064	0.210	6,622,560	1,380	11%
Fairbanks, AK (Sub -Artic)	84,501	4.1	20,610	0.204	6,433,344	1,340	7%
Houghton, MI (Very Cold)	61,778	4.1	15,068	0.204	6,433,344	1,340	9%
Los Angeles, CA (Hot-Dry)	20,250	4.4	4,602	0.210	6,622,560	1,380	30%
Knoxville, TN (Mixed-Humid)	44,861	4.4	10,196	0.205	6,464,880	1,347	13%
[1] Values from Table I.1							15%
[2] Values from Table H.6					Avg.	1,358	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	24	2%

Table I.62: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 81 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	17,611	4.3	4,096	0.000	0	0	0%
Arcata, CA (Marine)	10,667	4.1	2,602	0.000	0	0	0%
Austin, TX (Hot-Humid)	14,611	4.7	3,109	0.000	0	0	0%
Buffalo, NY (Cold)	22,417	4.2	5,337	0.000	0	0	0%
Fairbanks, AK (Sub -Artic)	39,584	4.1	9,655	0.000	0	0	0%
Houghton, MI (Very Cold)	28,167	4.1	6,870	0.000	0	0	0%
Los Angeles, CA (Hot-Dry)	7,639	4.4	1,736	0.000	0	0	0%
Knoxville, TN (Mixed-Humid)	16,917	4.4	3,845	0.000	0	0	0%
[1] Values from Table I.1							0%
[2] Values from Table H.6					Avg.	0	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	0	N/A

Table I.63: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 40 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	19,472	4.3	4,528	0.026	819,936	171	4%
Arcata, CA (Marine)	10,667	4.1	2,602	0.001	31,536	7	0%
Austin, TX (Hot-Humid)	21,778	4.7	4,634	0.043	1,356,048	283	6%
Buffalo, NY (Cold)	23,222	4.2	5,529	0.016	504,576	105	2%
Fairbanks, AK (Sub -Artic)	39,500	4.1	9,634	0.006	189,216	39	0%
Houghton, MI (Very Cold)	28,584	4.1	6,972	0.009	283,824	59	1%
Los Angeles, CA (Hot-Dry)	8,028	4.4	1,825	0.023	725,328	151	8%
Knoxville, TN (Mixed-Humid)	20,278	4.4	4,609	0.027	851,472	177	4%
[1] Values from Table I.1							3%
[2] Values from Table H.6					Avg.	124	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	84	68%

Table I.64: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IEC (2015) in-line fan, C_{HCHO} ≤ 16 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	26,772	4.3	6,226	0.108	3,405,888	710	11%
Arcata, CA (Marine)	14,667	4.1	3,577	0.070	2,207,520	460	13%
Austin, TX (Hot-Humid)	35,278	4.7	7,506	0.131	4,131,216	861	11%
Buffalo, NY (Cold)	30,167	4.2	7,183	0.093	2,932,848	611	9%
Fairbanks, AK (Sub -Artic)	47,889	4.1	11,680	0.075	2,365,200	493	4%
Houghton, MI (Very Cold)	35,750	4.1	8,720	0.080	2,522,880	526	6%
Los Angeles, CA (Hot-Dry)	11,167	4.4	2,538	0.110	3,468,960	723	28%
Knoxville, TN (Mixed-Humid)	29,556	4.4	6,717	0.107	3,374,352	703	10%
[1] Values from Table I.1							12%
[2] Values from Table H.6					Avg.	636	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	129	20%

Table I.65: Ventilation Fan Energy as a Percent of Total Energy – Ventilation using IECC (2015) in-line fan, C_{HCHO} ≤ 7 ppb, WC-2, DC mAER

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Avg. $Q_{mAER,n}$ m^3/s	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan[3] kWh_e/y	% annual electrical use by fan
Amarillo, TX (Mixed-Dry)	31,306	4.3	7,280	0.144	4,541,184	946	13%
Arcata, CA (Marine)	18,556	4.1	4,526	0.105	3,311,280	690	15%
Austin, TX (Hot-Humid)	41,306	4.7	8,789	0.167	5,266,512	1,097	12%
Buffalo, NY (Cold)	35,639	4.2	8,485	0.129	4,068,144	848	10%
Fairbanks, AK (Sub -Artic)	56,500	4.1	13,780	0.110	3,468,960	723	5%
Houghton, MI (Very Cold)	42,334	4.1	10,325	0.116	3,658,176	762	7%
Los Angeles, CA (Hot-Dry)	14,083	4.4	3,201	0.145	4,572,720	953	30%
Knoxville, TN (Mixed-Humid)	34,973	4.4	7,948	0.143	4,509,648	940	12%
[1] Values from Table I.1							13%
[2] Values from Table H.6					Avg.	870	
[3] Fan efficacy without HEPA/Carbon filter = 4800 m^3/kWh - IECC (2015)					σ / σ mean	130	15%

Table I.66: Ventilation Fan Energy as a Percent of Total Energy, ERV-A and HEPA/Carbon Filter, WC-2/AU, C_{HCHO} = 16 ppb

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan for HEPA/Carbon[3] kWh_e/y	Annual Electrical Energy Use by fans for ERV[4] kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by HEPA/Carbon fan	% annual electrical use by ERV fans
Austin, TX (Hot-Humid)	39,084	4.7	8,316	5,487,264	1,886	506	8,822	21%	6%

[1] Value from Table I.29

[2] Values from Table H.6

[3] Energy for HEPA/Carbon filter + 2 * Energy for ERV (balanced ventilation)

[4] 2 * fan Energy for ventilation rate through ERV (balanced ventilation)

Table I.67: Ventilation Fan Energy as a Percent of Total Energy, HEPA/Carbon Filter and GPF, WC-2/AU, C_{HCHO} = 16 ppb

Location (Climate Zone) T_{Clg} = 24.4 °C	Annual Energy Use[1] (Thermal only) kWh_{th}	Annual Avg. COP[2]	Annual Electrical Energy Use (Thermal only) kWh_e	Annual Ventilation Rate m^3/y	Annual Electrical Energy Use by fan for HEPA/Carbon[3] kWh_e/y	Annual GPF Airflow m^3/y	Annual Electrical Energy Use by fans for GPF kWh_e/y	Total Annual Electrical Energy Use kWh_e/y	% annual electrical use by HEPA/Carbon Ventilation fan	% annual electrical use by GPF fan
Austin, TX (Hot-Humid)	21,306	4.7	4,533	1,861,325	640	5,967,084	2,051	6,584	10%	31%

[1] Value from Table I.29

[2] Values from Table H.6

[3] Energy for HEPA/Carbon filter

References

ACGIH. (2010). *2010 Threshold Limit Values for Chemical Substances and Physical Agents & Biological exposure Indices*.

Aerodyne Research Inc. (2013). Formaldehyde Monitors. Retrieved from http://www.aerodyne.com/products/formaldehyde-monitors

AHRI. (2015). AHRI Directory. Retrieved from www.ahridirectory.org/ahridirectory/pages/erv/defaultSearch.aspx

AIA. (2014). Guidelines for Design and Construction of Hospital and Outpatient Facilities. The American Institute of Architects Press. Retrieved from http://www.fgiguidelines.org/digitalcopy.php

Aldred, J. R., Darling, E., Morrison, G., Siegel, J., & Corsi, R. (2015). Benefit-Cost Analysis of Commercially Available Activated Carbon Filters for Indoor Ozone Removal in Single-Family Homes. *Indoor Air*. http://doi.org/10.1111/ina.12220

ANSI/ASRHAE Standard 160-2009. (2009). Criteria for Moisture-control Design Analysis in Buildings. Atlanta, GA: ASHRAE.

ASHRAE. (2005). Ventilation and Infiltration. In *AHSRAE Handbook of Fundamentals*. Atlanta, GA: ASHRAE.

ASHRAE. (2010a). ANSI/ASHRAE Standards 62.2-2010 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, GA: ASHRAE.

ASHRAE. (2010b). ASHRAE Guideline 2-2010 Engineering Analysis of Experimental Data. Atlanta, GA: ASHRAE.

ASHRAE. (2010c). ASHRAE Standard 90.1-2010 Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, GA: ASHRAE.

ASHRAE. (2013a). ANSI/ASHRAE Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality. Atlanta, GA: ASHRAE.

ASHRAE. (2013b). ANSI/ASHRAE Standard 62.2-2013. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, GA: ASHRAE.

ASHRAE. (2013c). Chapter 1: Psychrometrics. In *Fundamentals*. Atlanta, GA: ASHRAE. Retrieved from http://handbook.ashrae.org/Handbook.aspx accessed 6/15/15

ASHRAE. (2013d). Chapter 14. Climate Design Conditions. In *ASHRAE Handbook, Fundamentals,*.

ASHRAE. (2013e). Chapter 18: Nonresidential cooling and heating load calculations. In *Handbook of Fundamentals*. Atlanta, GA: ASHRAE.

ASHRAE. (2013f). *Handbook of Fundamentals*. Atlanta, GA.

ASHRAE. (2016). ANSI/ASHRAE Standard 62.2-2016 Ventilation and Acceptable Infdoor Air Quality in Residential Buildings. Atlanta, GA: ASHRAE.

Association of Surgical Technologies. (2015). AST Guideline Statement on Humidity in the Operating Room. Retrieved October 4, 2016, from http://www.ast.org/uploadedFiles/Main_Site/Content/About_Us/Guideline_Statement_Humidity_in_the_OR.pdf

ASTM. (2006). ASTM E 741-00 (Reapproved 2006). Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. West Conshohocken, PA: ASTM.

ATSDR. (2004). *Guidance Manual for the Assessment of Joint Toxic Action of Chamical Mixtures*. Retrieved from http://www.atsdr.cdc.gov/interactionprofiles/IP-ga/ipga.pdf

ATSDR. (2015). ATSDR - Minimal Risk Levels for Hazardous Substances (MRLs). Retrieved August 7, 2015, from http://www.atsdr.cdc.gov/mrls/mrllist.asp

Baecheler, M. C., Williamson, J., Gilbride, T., Cole, P., Hefty, M., & Love, P. M. (2010). *Building America Best Practices Series, Volume 7.1 High-Performance Home Technologies: Guide to Determining Climate Regions by County, PNNL-17211*. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf

Baez, A. P., Padilla, H., Garcia, R., Belmont, R., & del Carmen Torres, M. (2006). Measurement of indoor-outdoor carbonyls at four residential homes in Mexico city metropolitan area. *Int. J. Environment and Pollution*, *26*(Nos. 1/2/3), 90–105.

Bell, M. L., Peng, R. D., Dominici, F., & Samet, J. M. (2009). Emergency Hospital Admissions for Cardiovascular diseases adn Ambient Levels of Carbon Monoxide Results from 126 United States Urban Counties, 1999-2005. *Circulation*, *120*, 949–955.

Berry, R. W., Brown, V. M., Coward, S. K. D., Crump, D. R., Gavin, M., Grimes, C. P., … Raw, G. J. (1996). *Indoor air quality in homes Part 1&2 The Building Research Establishment Indoor Environment Study*.

Bureau of Economic Analysis. (2015). Table 1.1.9. Implicit Price Deflotors for Gross Domestic Product. [Index numbers, 2009=100] Seasonally adjusted

Last Revised on: Spetember 25, 2015 - Next Release Date October 29, 2015. Retrieved from http://www.bea.gov/national/pdf/SNTables.pdf

CA EPA Air Resources Board. (2004). *Indoor Air Quality Guideline No.1: Formaldehyde in the Home*. Sacramento, CA. Retrieved from http://www.arb.ca.gov/research/indoor/formaldGL08-04.pdf

CA EPA Air Resources Board. (2007). Airborne Toxic Control Measure To Reduce Formaldehyde Emissions From Composite Wood Products. Retrieved from http://www.arb.ca.gov/regact/2007/compwood07/fro-final.pdf, accessed 7 June 2012

CA OEHHA. (2008). *Appendix D . Individual Acute , 8-Hour , and Chronic Reference Exposure Level Summaries. Formaldehyde Reference Exposure Levels*. Sacramento, CA. Retrieved from http://oehha.ca.gov/air/hot_spots/2008/AppendixD1_final.pdf#page=128

CA OEHHA. (2009). Appendix A : Hot Spots Unit Risk and Cancer Potency Values. Retrieved from http://www.oehha.ca.gov/air/hot_spots/tsd052909.html

CA OEHHA. (2013a). Chemicals Known To The State To Cause Cancer Or Reproductive Toxicity. Retrieved from http://www.oehha.ca.gov/prop65/prop65_list/files/P65single12272013.pdf

CA OEHHA. (2013b). Proposition 65 No Significant Risk Levels (NSRLs) for Carcinogens and Maximum Allowable Dose Levels (MADLs) for Chemicals Causing Reproductive Toxicity. Retrieved August 12, 2015, from http://oehha.ca.gov/prop65/pdf/safeharbor081513.pdf

CA OEHHA. (2014a). All OEHHA Acute, 8-hour and Chronic Reference Exposure Levels (chRELs) as on June 2014. Retrieved from http://oehha.ca.gov/air/allrels.html

CA OEHHA. (2014b). Appendix D. individual Acute, 8-hour, and Chronic Reference Exposure Level Summaries. Retrieved July 8, 2015, from http://oehha.ca.gov/air/hot_spots/2008/AppendixD1_final.pdf#page=5

CA OEHHA. (2015a). Chemicals known to the state to cause cancer or reproductive toxicity. Retrieved July 8, 2015, from http://oehha.ca.gov/prop65/prop65_list/files/P65single061915.pdf

CA OEHHA. (2015b). Notices of Intent to List Chemicals. Retrieved August 17, 2015, from http://oehha.ca.gov/prop65/CRNR_notices/admin_listing/intent_to_list/index.html

Caldwell, J. B., & Milligan, B. (1972). the Sites of reaction of Wool with Formaldehyde. *Textile Research Journal*, *42*(2), 122–124.

Carter, E. M. (2013). *Removal of Formaldehyde from Indoor Air: Enhancing Surface-Mediated Reactions on Activated Carbon*. The University of Texas at Austin.

Carter, E. M., Jackson, M. C., Katz, L. E., & Speitel, G. E. (2013). A coupled sensor-spetrophotometric device for continuous measuremnet of formaladehyde in indoor environments. *Journal of Exposure Science and Environmental Epidemiology*, *1–6*. http://doi.org/10.1038/jes.2013.61 [Epub ahead of print]

Carter, E. M., Katz, L. E., Speitel, G. E., & Ramirez, D. (2011). Gas-Phase Formaldehyde Adsorption Isotherm Studies on Activated Carbon: Correlations of Adsoprtion Capacity to Surface Functional Group Density. *Environemntal Science & Technology*, *45*, 6498–6503.

CGSB. (1986). CAN/CGSB 149.10-M48 Detemination of the Airtightness of Building Envelopes by the Fan Depressurization Method. Gatineau, Quebec, Canada. Retrieved from https://www.scc.ca/en/standardsdb/standards/3214

Chen, C. Y., Mistry, J., Fung, A. S., Leong, W. H., & Jhingan, S. (2012). Design and Analysis of an Integrated Heat and Energy Recovery Ventilation System with Economizer Control for Net-Zero Energy Solar Homes, SA-12-C011. *ASHRAE Transactions*. ASHRAE.

Cheng, M., Galbally, I. E., Molloy, S. B., Selleck, P. W., Keywood, M. D., Lawson, S. J., … Dunne, E. (2015). Factors controlling volatile organic compounds in dwellings in Melbourne, Australia. *Indoor Air*, *Accepted*. http://doi.org/doi: 10.1111/ina.12201

Climate Policy Initiative. (2015). California Carbon Dashboard. The latest on emissions policy and cap and trade in the world’s 14th largest emitter. Retrieved December 10, 2015, from http://calcarbondash.org/

CO2 Now. (2015). Atmospheric CO2 / NOAA-ESRL, Monthrly Mean Concentrtations at Mauna Loa Observatory. Data update released fy NOAA-ESRL October 5, 2015. Retrieved December 10, 2015, from http://co2now.org/images/stories/data/co2-mlo-monthly-noaa-esrl.pdf

Corfield, M. C., & Robson, A. (1955). The amino acid composition of wool. *The Biochemical Journal*, *59*(1), 62–8. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1216090&tool=pmcentrez&rendertype=abstract

Corsi, R.L., Aldred, J.R., Darling, E.K., Siegel, J.A., Morrison, G. C. (2014). *ASHRAE Research Project Report 1491-RP. Literature and Product Review and Cost Benefit Analysis of Commercially Avaiable Ozone Air Cleaning for HVAC Systems*.

CPSC. (2013). *Carbon Monoxide Alarm Conformance Testing to UL2034:*

Standard for Safety for Carbon Monoxide Alarms. Rockville, MD. Retrieved from http://www.cpsc.gov/global/research-and-statistics/technical-reports/home/carbon-monoxide/coalarmconformancereportfy 2013clearedtechreport.pdf

Cros, C. J., Morrison, G. C., Siegel, J. A., & Corsi, R. L. (2012). Long-term performance of passive materials for removal of ozone from indoor air. *Indoor Air*, *22*(1), 43–53. http://doi.org/10.1111/j.1600-0668.2011.00734.x

Dannemiller, K. C., Murphy, J. S., Dixon, S. L., Pennell, K. G., Suuberg, E. M., Jacobs, D. E., & Sandel, M. (2013). Formaldehyde concentrations in household air of asthma patients determined using colorimetric detector tubes. *Indoor Air*, *23*, 285–294.

DC Group International. (2013). DC Group International. Retrieved from www.dcgroupinternational.com, accessed 10/29/13

Deore, B., Diaz-Quijada, G. A., Wayner, D. D. M., Steward, D., Won, D., & Waldron, P. (2011). An Electronic Nose for Detection of Carbonyl Species. *ECS Transactions*, *35*(7), 83–88.

Derundi, M., Gelosa, S., Sliepcevich, A., Cattaneo, A., Cavallo, D., Rota, R., Nano, G. (2014). Emission of air pollutants from burning candles with different composition in indoor environments. *Environ Sci Pollut Res*, *21*, 4320–4330.

Dunford, J., Tunney, J. J., & Du, X. (2010). SnO2/NiO Composite Thin Films for Formaldehyde Detection. In *IEEE SENSORS 2010 Conference* (pp. 1500–1503).

EnergyPlus(TM). (2012). *EnergyPlus Engineering Reference, The Reference to EnergyPlus Calculations (in case you want or need to know), October 6, 2012*.

Ernstgård, L., Iregren, A., Sjögren, B., & Johanson, G. (2006). Acute effects of exposure to vapours of acetic acid in humans. *Toxicology Letters*, *165*(1), 22–30. http://doi.org/10.1016/j.toxlet.2006.01.010

Ewlad-Ahmed, A. M., Morris, M. A., Patwardhan, S. V, & Gibson, L. T. (2012). Removal of formaldehyde from air using functionalized silica supports. *Environmental Science & Technology*, *46*(24), 13354–60. http://doi.org/10.1021/es303886q

FEMA. (2008a). FEMA Statement on Formaldehyde. Retrieved from http://www.fema.gov/news/newsrelease.fema?id=44961

FEMA. (2008b). New FEMA Procurement Specifications Require Significantly Reduced Formaldehyde Levels In Mobile Homes And Park Models. Retrieved from http://www.fema.gov/news/newsrelease.fema?id=43180

Fisk, W. J., Destaillats, H., & Sidheswaran, M. A. (2011). Saving Energy and Improving IAQ through Application of Advanced Air Cleaning Technologies. *REHVA Journal*, (May), 27–29.

Francisco, P. W., Gordon, J. R., & Rose, B. (2010). Measured concentrations of combustion gases from the use of unvented gas fireplaces. *Indoor Air*, *20*, 370–379.

Frihart, C. R., Wescott, J. M., Chaffee, T. L., & Gonner, K. M. (2012). Formaldehyde Emissions from Urea-Formaldehyde and No-Added_Formaldehyde-Bonded Pareticleboard as Influenced by Temperature and Relative Humidity. *Forest Products Journal*, *62*(7/8), 551–558. Retrieved from http://originwww.fpl.fs.fed.us/documnts/pdf2012/fpl_2012_frihart001.pdf

Gall, E., Darling, E., Siegel, J. A., Morrison, G. C., & Corsi, R. L. (2013). Evaluation of three common green building materials for ozone removal, and primary and secondary emissions of aldehydes. *Atmospheric Environment*, *77*, 910–918.

Gatley, D. P. (2005). *Understanding Psychrometrics* (2nd ed.). Atlanta, GA: ASHRAE.

Ghosh, A., & Collie, S. (2014). Keratinous Materials as Novel Absorbent Systems for Toxic Pollutants. *Defence Science Journal*, *64*(3), 209–221. http://doi.org/10.14429/dsj.64.7319

Gilbert, N. L., Guay, M., Gauvin, D., Dietz, R. N., Chan, C. C., & Levesque, B. (2008). Air change rate and concentration of formaldehyde in residential indoor air. *Atmospheric Environment*, *42*(10), 2424–2428. http://doi.org/10.1016/j.atmosenv.2007.12.017

Grandjean, P., & Landrigan, P. J. (2014). Neurobehavioral effects of developmental toxcity. *Lancet Neurology*, *13*, 330–38. Retrieved from http://www.thelancet.com/journals/laneur/article/PIIS1474-4422(13)70278-3/abstract

Grűtzner, T., & Hasse, H. (2004). Solubility of Formaldehyde and Triozane in Aqueous Solutions. *J. Chem. Eng. Data*, *49*, 642–646.

Han, K., Guo, B., Pei, J., & Zhang, J. (2012). *Energy-Efficienct reduction of Indoor Formaldehyde Exposure by Dynamic Integration of Air-Cleaning and Ventilation*. Syracuse, NY.

Hawthorne, A. R., Gammage, R. N., Dudney, C. S., Hingerty, B. E., Schuresko, D. D., Parzyck, D. C., … Schrimsher, J. M. (1984). *An Indoor Air Quality Study of Forty east Tennessee Homes, ORNL-5965*. Oak Ridge.

Health Canada. (2006). Residential Indoor Air Quality Guideline : Formaldehyde Environmental and Workplace Health Residential Indoor Air Quality

Guideline : Formaldehyde Residential Indoor Air Quality Guideline : Formaldehyde Page 2 of 3. Retrieved from http://www.hc-sc.gc.ca/ewh-semt/pubs/air/formaldehyde-eng.php

Healthy Building Network. (2014). Pharos Project. Retrieved from http://www.healthybuilding.net/content/pharos-v3

Hendron, R., & Engebrecht, C. (2010). *Building Ameica house simulation protocols, Report TP-550-49426*. Golden, Colorado. Retrieved from http://www.nrel.gov/docs/fy11osti/49246.pdf

Home Ventilating Institute. (2017). HVI Publication 911:Certified Home Ventilation Products Directory Section III - HRV/ERV Directory Listing, Current as of April 21, 2017. Retrieved April 24, 2017, from https://www.hvi.org/proddirectory/CPD.Reports/section_3/index.cfm

Huijbregts, M. A. J., Rombouts, L. J. A., Raga, A. M. J., & van de Meent, D. (2005). Human-Toxicological Effect and Damage Factors of Carcinogenic and Noncarcinogenic Chemicals for Life Cycle Impact Assessment. *Integrated Environmental Assessment and Management*, *1*(3), 181–244.

Huizing, R., Chen, H., & Wong, F. (2013). Contaminant Transport in Membrane Based Energy Recovery Ventilators. In *ASHRAE IAQ 2013 Proceedings: Environmental Health in Low Energy Buildings* (p. Paper #78). Vanouver: ASHRAE.

Huizing, R., & Kadylak, D. (n.d.). Personal communication.

Hult, E.L., Willem, H., Peie, P.N., Hotchi, T., Russell, M.L., Singer, B. C. (2015). Formaldehyde and acetaldehyde exposure mitigation in US residences: in-home measurements of ventilation control and source control. *Indoor Air*, *25*, 523–535.

Hult, E.L., Willem, H., Sherman, M. H. (2014). Formaldehyde transfer in residential energy recovery ventilators. *Building and Environment*, *75*, 92–97.

Hun, D. E., Corsi, R. L., Morandi, M. T., & Siegel, J. A. (2010). Formaldehyde in residences: long-term indoor concentrations and influencing factors. *Indoor Air*, *20*(3), 196–203. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20408902

Hun, D. E., & Jackson, M. C. (2014). *Intermittent Ventilation Energy Demands and Indoor Air Quality in Mixed-Humid Climates, ORNL/TM-2014/136*. Oak Ridge.

Hun, D. E., Jackson, M. C., & Shrestha, S. S. (2013a). *Optimization of Ventilation Energy Demands in ZEBRAlliance Homes, ORNL/TM-2013/275*. Oak Ridge.

Hun, D. E., Jackson, M. C., & Shrestha, S. S. (2013b). Ventilation Energy

Demands and Indoor Air Quality in High-Performance Homes. *Interface*, *31*(9), 39–46.

Hun, D. E., Shrestha, S. S., & Jackson, M. C. (2014). Optimization of Ventilation Energy Demands and Indoor Air Quality in High-Performance Homes. In *ACEEE Summer Study on Energy Efficiency in Buildings The Next generation: Reaching for High Energy Savings* (pp. 1-121-132). Retrieved from http://aceee.org/files/proceedings/2014/data/index.htm

Hun, D. E., Siegel, J. A., Morandi, M. T., & Corsi, R. L. (2009). Effect of ventilation rates on indoor formaldehyde concentrations in residences. *Buildings*, (2005), 2–5.

Hurel, N., Sherman, M. H., & Walker, I. S. (2015). *Simplified Methods for Combining Natural and Mechanical Ventilation, LBNL-184001*. Berkeley, CA.

IARC. (2004). IARC classifies formaldehyde as carcinogenic to humans; press release no. 153, International Agency for Research on Cancer. Retrieved from http://www.iarc.fr/en/media-centre/pr/2004/pr153.html

IECC. (2009). Residential Prescriptive Requirements 2009 International Energy Conservation Code (IECC). Retrieved from http://energycode.pnl.gov/EnergyCodeReqs/

IECC. (2015). 2015-IECC International Energy Conservation Code.

IFRA. (2011). IFRA Fragrnce Ingredients list. Retrieved November 4, 2014, from http://www.ifraorg.org/en-us/ingredients#.U0gmdjdOW1t

IPCS INCHEM. (1994). OECD Screening Information DataSet (SIDS) High Production Volume Chemicals. Retrieved September 9, 2016, from http://www.inchem.org/documents/sids/sids/100527.pdf

Jackson, M. C., Penn, R. L., Cude, G. E., Neace, L. M., & Kuhs, J. F. (2011). Formaldehyde : How Low Can We Go ? In *Proceedings of IndoorAir 2011* (p. a136_6). Austin, TX.

Jackson, M. C., Penn, R. L., Cude, G. E., Neace, L. M., & Kuhs, J. F. (2011). Formaldehyde : How Low Can We Go ? In *IndoorAir 2011* (p. a136_6). Austin, TX.

Jimenez, R., Herndon, S., Shorter, J. H., Nelson, D. D., McManus, J. B., & Zahniser, M. S. (2005). Atmospheric trace gas measurmenets using a dual quantum-cascade laser mid-infrared absorption spectrometer. In *Proc. of SPIE* (p. Vol 5738, 318-331). Bellingham, WA.

Kadylak, D. (2015). Personal Communication 2 April 2015.

Kodama, A. (2010). Cross-Contamination Test of an Enthalpy Wheel Loading a Strong Acidic Cation Ion-Exchange Resin or 3A Zeolite as a Desiccant

Material. *Journal of Chemical Enginering of Japan*, *43*(10), 901–905.

Kunkel, S., Kontonsasiou, E., Arcipowsha, A., Mariottini, F., & Atanasiu, B. (2015). *Indoor Air Quality, Thermal Comfort and Daylight: Analysis of Residential Building Regulations in Eight EU Member States*. Brussels. Retrieved from www.bpie.eu

Less, B., Mullen, N., Singer, B., & Walker, I. S. (2015). Indoor air quality in 24 California residences designed as high-performance homes. *Science and Technology for the Built Environment*, *21*(1), 14–24. http://doi.org/10.1080/10789669.2014.961850

Logue, J. M., Klepeis, N. E., Lobscheid, A. B., & Singer, B. C. (2014). Pollutant Exposures from Natural Gas Cooking Burners: A Simulation-Based Assessment for Southern California. *Environmental Health Perspectives*, *122*(1), 43–50. Retrieved from http://ehp.niehs.nih.gov/1306673/

Logue, J. M., McKone, T. E., Sherman, M. H., & Singer, B. C. (2011). Hazard assessment of chemical air contaminants measured in residences. *Indoor Air*, *21*(2), 92–109.

Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. . (2011). *A Method to Estimate the Chornic Health Impact of Air Pollutants in U.S. Residences, LBNL Report Number 5267-E*. Berkeley, CA.

Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A Method to Estimate the Chronic Health Impact of Air Pollutants. *Environmental Health Perspectives*, *120*(2), 216–222. Retrieved from http://ehp03.niehs.nih.gov/article/fetchArticle.action?articleURI=info%3Adoi%2F10.1289%2Fehp.1104035

Luttrell, W. E. (2012). Acetic acid. *Journal of Chemical Health and Safety*, *19*(6), 37–38. http://doi.org/10.1016/j.jchas.2012.09.008

Malkin-weber, M. (2009). Formaldehyde in High Performance Homes with Outdoor Air Intakes.

Malkin-Weber, M., Coulter, J., Dixon, T., Hannas, B., & Hassel, S. (2009). Measured Formaldehyde in High Performance Homes with Outdoor Air Intakes. In *Indoor Air Quality Association 12th Annual Meeting*. Fort Worth, TX: Indoor Air Quality Association.

Mandin, C., Bonvallot, N., Kirchner, S., Keirsbulck, M., Alary, R., Cabanes, P., Dor, F., LeMoullec, Y., Mullot, J., Peel, A., Rousselle, C. (2009). Development of French Indoor Air Quality Guidelines. *Clean*, *37*(6), 494–499.

Maruo, Y. Y., & Nakamura, J. (2011). Portable formaldehyde monitoring device using porous glass sensor and its applications in indoor air quality studies.

Analytica Chimica Acta, *702*(2), 247–53. http://doi.org/10.1016/j.aca.2011.06.050

Maruo, Y. Y., Nakamura, J., & Uchiyama, M. (2008). Development of formaldehyde sensing element using porous glass impregnated with beta-diketone. *Talanta*, *74*(5), 1141–1147. http://doi.org/10.1016/j.talanta.2007.08.017

Maruo, Y. Y., Nakamura, J., Uchiyama, M., Higuchi, M., & Izunli, K. (2008). Development of formaldehyde sensing element using porous glass impregnated with Schiff's reagent. *Sensors and Actuators B-Chemical*, *129*(2), 544–550. http://doi.org/10.1016/j.snb.2007.09.002

Maruo, Y. Y., Yamada, T., & Nakamura, J. (2009). Sensor Element for Indoor Formaldehyde Measurement. *NTT Technical Review*, *7*(10), 1–5.

Maruo, Y. Y., Yamada, T., Nakamura, J., Izumi, K., & Uchiyama, M. (2010). Formaldehyde measurements in residential indoor air using a developed sensor element in the Kanto area of Japan. *Indoor Air*, *20*(6), 486–493. http://doi.org/10.1111/j.1600-0668.2010.00670.x

Matthews, T. G., Fung, K. W., Tromberg, B. J., & Hawthorne, A. R. (1986). Impact of Indoor Environmental Parameters on Formaldehyde Concentrations in Unoccupied Research Houses. *Journal of the Air Pollution Control Association*, *36*, 1244–1249.

Matthews, T. G., Hawthorne, a R., & Thompson, C. V. (1987). Formaldehyde sorption and desorption characteristics of gypsum wallboard. *Environmental Science & Technology*, *21*(7), 629–34. http://doi.org/10.1021/es00161a002

Miller, W., Kosny, J., Shrestha, S., Christian, J., Karagiozis, A., Kohler, C., & Dinse, D. (2010). Advanced Residential Envelopes for Two Pair of Energy-Saver Homes. In *Proceedings from the ACEEE Summer Study on Energy Efficiency in Buildings, 15-20 August 2010*. Pacific Grove, CA: ACEEE. Retrieved from http://www.zebralliance.org/pdfs/ZEBRA Demonstration Report.pdf

Miller, W., Shrestha, S., Childs, K., & Stannard, E. (2012). Field Study and Energy-Plus Benchmarks for energy Saver Homes Having Different Envelope Designs. Retrieved from http://www.zebralliance.com/pdfs/ZEBRA Envelope II ACEEE 2012.pdf

Mlade, J., Farrha, K., Glazer, B., Roose, C., Syrett, P., Youssef, C., & Buller, K. (2011). *Healthy Environments A Compilation of Substances Linked to Asthma*. Atlanta, GA.

Moore, F. C., & Diaz, D. B. (2015). Temperature impacts on economic growth warrant stringent mitgation policy. *Nature Climate Change*, *5*, 127–131. Retrieved from http://www.nature.com/nclimate/journal/v5/n2/full/nclimate2481.html

Moragues, M. E., Montes-Robles, R., Ros-Lis, J. V., Alcañíz, M., Ibañez, J., Pardo, T., & Martínez-Máñez, R. (2014). An optoelectronic sensing device for CO detection in air based on a binuclear rhodium complex. *Sensors and Actuators B: Chemical*, *191*, 257–263. http://doi.org/10.1016/j.snb.2013.09.107

Moragues, M. E., Toscani, A., Sancenón, F., Martínez-Máñez, R., White, A. J. P., & Wilton-Ely, J. D. E. T. (2014). A chromo-fluorogenic synthetic "canary" for CO detection based on a pyrenylvinyl ruthenium(II) complex. *Journal of the American Chemical Society*, *136*(34), 11930–3. http://doi.org/10.1021/ja507014a

Mumma, S. A. (2010). DOAS & Building Pressurization. *ASHRAE Journal*, (August), 42–52.

Mumtaz, M., E. (2010). *Principles and Practice of Mixtures Toxicoogy*. Weinheim: Wiley-VCH.

NAS. (2011). *Review of the Environmental Protection Agency's Draft IRIS Assessment of Formaldehyde*. The National Academies Press. Retrieved from http://www.nap.edu/openbook.php?record_id=13142

National Environmental Protection Council. (2013). *Annual Report 2012-1013*. Canberra, Australia. Retrieved from http://www.scew.gov.au/system/files/resources/bb58c8a4-bc71-4c85-bb18-dc8c597bde2b/files/nepc-annual-report-2012-13.pdf , accessed 3/29/15

National Environmental Protection Council Service Corporation. National Environment Protection (Air Toxics) Measure (2011). Retrieved from http://www.comlaw.gov.au/Details/F2011C00855 , accessed 3/29/15

National Library of Medicine. (2014). BENZALDEHYDE. Retrieved July 8, 2015, from http://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+388

Nielsen, G. D., & Wolkoff, P. (2010). Cancer effects of formaldehyde: A proposal for an indoor air guideline value. *Archiv Toxicol*, *84*, 423–46.

Nirlo, E.L., Crain, N., Corsi, R.L., Siegel, J. A. (2015). Field evaluation of five volatile organic compound measurement techniques: Implications for gren building decision making. *Science and Technology for the Built Environment*, *21*(1), 67–69.

Nittler, K., & Wilcox, B. (2006). *Residential Housing Starts and Prototypes, 2008 Californian Building Energy Efficiency Standards*. Retrieved from http://www.energy.ca.gov/title24/2008standards/prerulemaking/documents/2006-03-28_workshop/2006-03-27_RES_STARTS-PROTOTYPES.PDF

NOAA. (2015). Trends in Atomospheric Carbon Dioxide. Retrieved March 4, 2015, from http://www.esrl.noaa.gov/gmd/ccgg/trends/

Nomura, A., & Jones, C. W. (2015). Airborne Aldehyde Abatement by Latex Coatings Containing Amine-Functionalized Porous Silicas. *Industrial & Engineering Chemistry Research*, *54*(1), 263–271. http://doi.org/10.1021/ie504165d

NRCC. (2011). Highlights - E-nose smells new applications. Retrieved from http://archive.nrc-cnrc.gc.ca/eng/news/nrc/2011/09/01/enose-sims.html

OECD. (2013a). *“Climate and Carbon: Aligning Prices and Policies”, OECD Environmental Policy Papers, No. 1*. Paris: OECD Publishing. Retrieved from http://www.oecd-ilibrary.org/docserver/download/5k3z11hjg6r7.pdf?expires=1444953409&id=id&accname=guest&checksum=293E3004D65944DED540B687FB552BD0

OECD. (2013b). Putting a Price on Carbon with a Tax. Retrieved from http://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf

Offermann, F. (2009). *Ventilation and indoor air quality in new homes. Collaborative Report. CEC-500-2009-085. PIER Energy-Related Environmental Research Program.* Sacramento, CA: California Air Resources Board and California Energy Commission.

Offermann, F. (2010). IAQ in Airtight Homes. *ASHRAE Journal*, (November), 58–60.

Pei, J., & Zhang, J. (2011). Critical review of catalytic oxidation and chemisorption methods for indoor formaldehyde removal. *HVAC&R Research*, *17*(4), 1938–5587.

Persily, A. (2006). What we Think we Know about Ventilation. *International Journal of Ventilation*, *5*(3), 1473–3315.

Persily, A., Musser, A., & Emmerich, S. J. (2010). Modeled infiltration rate distributions for U.S. housing. *Indoor Air*, *20*, 473–485.

Plaisance, H., Blondel, A., Desauziers, V., & Mocho, P. (2013). Field investigation on the removal of formaldehyde in indoor air. *Building and Environment*, *70*, 277–283. http://doi.org/10.1016/j.buildenv.2013.08.032

Pohl, H. R., Roney, N., Wilbur, S., Hansen, H., & De Rosa, C. (2003). Six interaction profiels for simple mixtures. *Chemosphere*, *53*, 183–197. Retrieved from https://www.researchgate.net/publication/10633783_Six_interaction_profiles_for_simple_mixtures

Poppendieck, D. (2016). Personal communication.

Poppendieck, D., Hubbard, H., Ward, M., Weschler, C., & Corsi, R. L. (2007). Ozone reactions with indoor materials during building disinfection. *Atmospheric Environment*, *41*, 3166–3176.

Poppendieck, D., Khurshid, S., Dols, W., Ng, L., Polidoro, B., & Emmerich, S. (2016). Formaldehyde Concentrations in a Net-Zero House: real-time Monitoring and Simulation. In *14th International Conference on Indoor Air Quality and Climate Conference*. Ghent: ISIAQ.

Rackes, A. and Waring, M. S. (2016). Do time-averaged, whole-building, effective volatile organic compound (VOC) emissions depend on the air exchange rate? A statistical analysis of trends for 46 VOCs in U.S. offices. *Indoor Air*, *26*(4), 642–659.

RESNET. (2006). 2006 Mortgage Industry National Home Energy Rating Systems Standards. Retrieved from http://resnet.us/standards/RESNET_Mortgage_Industry_National_HERS_Standards.pdf

RESNET. (2012). Proposed RESNET Standard 301-CD01: Standard for the Calculation and Labeling of the Energy Performance of Low-Rise residential Buildings using the HERS Index. Retrieved from http://resnet.us/professional/standards/proposed_consensus_standards

Rumchev, K. B., Spickett, J. T., Bulsara, M. K., Phillips, M. R., & Stick, S. M. (2002). Domestic exposure to formaldehyde significantly increases the risk of asthma in young children. *Eur Respir J*, *20*, 403–408.

Russell, L. D. (2015). Personal Communication, History of DC Group International Inc.

Salthammer, T. (2013). Formaldehyde in the Ambient Atmosphere: From an Indoor Pollutant to an Outdoor Pollutant? *Angew. Chem. Int. Ed.. Chem. Int. Ed.*, *52*, 3320–3327.

Salthammer, T., Mentese, S., & Marutzky, R. (2010). Formaldehyde in the indoor environment. *Chemical Reviews*, *110*(4), 2536–72. http://doi.org/10.1021/cr800399g

Sassine, M., Picquet-Varrault, B., Perraudin, E., Chiappini, L., Doussin, J. F., & George, C. (2013). A new device for formaldehyde and total aldehydes real-time monitoring. *Environ Sci Pollut Res*, (Online).

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance. *Environmental Health Perspectives*, *120*(12), 1671–1677. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3548274/ (accessed 7/20/14)

Sekine, Y. (2002). Oxidative decomposition of formaldehyde by metal oxides at room temperature, *36*, 5543–5547.

Sekine, Y., & Nishimura, A. (2001). Removal of formaldehyde from indoor air by passive type air-cleaning materials. *Atmospheric Environment*, *35*(2001), 2001–2007.

Sherman, M. (2015). How ASHRAE Set the Rate For Residential Ventilation. *ASHRAE Journal*, (July), 22–25.

Sherman, M. H. (2004). *Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality, LBNL 56292*. Berkeley. Retrieved from http://www-epb.lbl.gov/publications/pdf/lbnl-56292.pdf

Sherman, M. H. (2006). Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality. *ASHRAE Transactions*, *112*(1).

Sherman, M. H. (2016). Personal communication.

Sherman, M. H., & Hodgson, A. T. (2004). Formaldehyde as a basis for residential ventilation rates. *Indoor Air*, *14*(1), 2–8. Retrieved from http://doi.wiley.com/10.1046/j.1600-0668.2003.00188.x

Sherman, M. H., Mortensen, D. K., & Walker, I. S. (2011). Derivation of equivalent continuous dilution for cyclic, unsteady driving forces. *International Journal of Heat and Mass Transfer*, *54*(11–12), 2696–2702. http://doi.org/10.1016/j.ijheatmasstransfer.2010.12.018

Sherman, M. H., & Walker, I. S. (2011). Meeting residential ventilation standards through dynamic control of ventilation systems. *Energy and Buildings*, *43*(8), 1904–1912. http://doi.org/10.1016/j.enbuild.2011.03.037

Shields, K. N., Cavalleri, J. M., Hunt, M. J. O., Lazo, M., Molina, M., Molina, L., & Holfuin, F. (2013). Traffic-related air pollution exposures and changes in heart rate variability in Mexico City: A panel study. *Environmental Health*, *12*(7), 1–14. Retrieved from http://www.ehjournal.net/content/12/1/7

Shinyei Technology Co. (2011). Formaldehyde Multimode Monitor. Retrieved from http://www.shinyei.co.jp/stc/eng/iaq/formaldehyde.html

Shrestha, S. S. (2013). Personal communication.

Sidheswaran, M. A., Destaillats, H., & Sullivan, D. P. (2012). Energy efficient indoor VOC air cleaning with activated carbon fiber (ACF) filters. *Building and Environment*, *47*, 357–367.

Sidheswaran, M. A., Destaillats, H., Sullivan, D. P., Larsen, J., & Fisk, W. J. (2011). Quantitative room-temperature mineralization of airborne formaldehyde using manganese oxide catalysts. *Applied Catalysis B: Environmental*, *107*(1–2), 34–41. http://doi.org/10.1016/j.apcatb.2011.06.032

Sidheswaran, M., Cohn, S., Sullivan, D. P., & Gundel, L. A. (2013). *Performance Evaluation of Real Time Formaldehyde Monitors: PTR-MS and Interscan 4160-500B Portable Monitor*. Berkeley. Retrieved from http://eetd.lbl.gov/sites/all/files/lbnl-6357e.pdf

Sidheswaran, M., Destaillats, H., Cohn, S., Sullivan, D. P., & Fisk, W. J. (2011). *New Air Cleaning Strategies for Reduced Commercial Building Ventilation energy - FY11 Final Report, LBNL-5264E*. Berkeley, CA.

Singer, B. C., & Willem, H. (2012). Formaldehyde in New Homes Ventilation vs . Source Control, PPT Presentation. In *Building America Residential Stakeholder Meeting, March 1, 2012*. Austin, TX.

Slob, W. (1994). No Title. *Risk Analysis*, *14*(4), 571–576.

Spadaro, J. V., & Rabl, A. (2008). Estimating the uncertainty of damage costs of pollution: A simple transparent method and typical results. *Environ. Impact Assess. Rev.*, *28*, 166–183.

Sundell, J., Levin, H., Nazaroff, W. W., Cain, W. S., Fisk, W. J., Grimsrud, D. T., … Weschler, C. J. (2011). Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air*, *21*, 191–204.

TCEQ. (2014). *March 2014 Effects Screening Levels*. Austin, TX. Retrieved from https://www.tceq.texas.gov/toxicology/esl

TCEQ. (2015). *September 2015 Effects Screening Levels*. Austin, TX. Retrieved from https://www.tceq.texas.gov/toxicology/esl/list_main.html

The Engineering Toolbox. (2015). The Engineering ToolBox, Enthalpy of Moist and Humid Air. Retrieved July 11, 2015, from http://www.engineeringtoolbox.com/enthalpy-moist-air-d_683.html

The Engineering Toolbox. (2017). The Engineering Toolbox, Fans - Efficiency and Power Consumption. Retrieved from http://www.engineeringtoolbox.com/fans-efficiency-power-consumption-d_197.html

Traynor, G. W., Anthon, D. W., & Hollowell, C. D. (1982). Technique for determining pollutant emissions from a gas-fired range. *Atmospheric Environment (1967)*, *16*(12), 2979–2987. http://doi.org/10.1016/0004-6981(82)90049-X

Turner, W. J. N., Logue, J. M., & Wray, C. P. (2013). A combined energy and IAQ assessment of the potential value of commisisioning residential mechanical ventilation systems. *Buiilding and Environment*, *60*, 194–201.

U.S. Congress. Formaldehyde Stadards For Composite Wood Products (2010). Retrieved from http://www.gpo.gov/fdsys/pkg/BILLS-111s1660enr/pdf/BILLS-111s1660enr.pdf, accessed 7 June 2012

U.S. CPSC. (2013). An Update on Formaldehyde. Retrieved from http://www.cpsc.gov/PageFiles/121919/AN UPDATE ON FORMALDEHYDE final 0113.pdf

U.S. DHHS. (2011). *Report on Carcinogens Twelfth Edition*. Retrieved from http://ntp.niehs.nih.gov/ntp/roc/twelfth/roc12.pdf

U.S. DHHS. (2014). Report on Carcinogens, Thirteenth Edition. Retrieved July 8, 2015, from http://ntp.niehs.nih.gov/pubhealth/roc/roc13/index.html

U.S. DHHS, CDC, & NIOSH. (2013). Update of NIOSH Carcinogen Classification and Target Risk Level Policy for Chemical Hazards in the Workplace. External Review Draft. Retrieved from http://www.cdc.gov/niosh/docket/review/docket240A/pdf/EID-CIB-11052013.pdf

U.S. DOE Building Technology Office. (2012). EnergyPlus(TM), v. 7.2.0.006. Retrieved from https://energyplus.net/

U.S. EIA. (2003). Commercial Buildings Energy Consumptoin Survey (CBECS). Retrieved from http://www.eia.gov/consumption/commercial/census-maps.cfm#census

U.S. Energy Information Administration. (2015). Electric Power Monthly with Data for July 2015. Retrieved December 10, 2015, from http://www.eia.gov/electricity/monthly/pdf/epm.pdf

U.S. EPA. (1991). Acetaldehyde. Retrieved July 8, 2015, from http://www.epa.gov/iris/subst/0290.htm

U.S. EPA. (1999). Compendium of Methods for the Detemrination of Toxic Organic Compounds in Ambient Air, Second Edition, Compendium Method TO-11A, Determination of Formaldehyde in Ambeient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HP. Retrieved from http://www.epa.gov/ttnamti1/files/ambient/airtox/to-11ar.pdf

U.S. EPA. (2003a). Integrated Risk Information System, Benzene. Retrieved July 8, 2015, from http://www.epa.gov/iris/subst/0276.htm

U.S. EPA. (2003b). Method 8015D Nonhalogenated organics using GC/FID, Revision 4. Retrieved August 14, 2015, from http://www.epa.gov/osw/hazard/testmethods/pdfs/8015d_r4.pdf

U.S. EPA. (2006). Environmental Specifications - Section 01445. Testing for indoor Air Quality, Baseline IAQ, and Materials. Retrieved from http://web.archive.org/web/20061015003607/http://www.epa.gov/rtp/new-bldg/environmental/s_01445.htm

U.S. EPA. (2011). *Exposure Factors Handbook: 2011 Edition; EPA/600/R-090/052F*. Washington, DC. Retrieved from http://www.epa.gov/ncea/efh/pdfs/efh-complete.pdf accessed 5/28/15

U.S. EPA. (2012a). Formaldehyde (CASRN 50-00-0). Retrieved from http://www.epa.gov/iris/subst/0419.htm#refinhal

U.S. EPA. (2012b). How to use eBRID for Carbon Footprinting Electricity Purchases in Greenhouse Gas Emission Inventories. Retrieved December 10, 2015, from http://www2.epa.gov/sites/production/files/2015-01/documents/adiem.pdf

U.S. EPA. (2013). *Moisture Control Guidance for Building Design, Construction and Maintenance, EPA402-F-13053*. Washington, DC. Retrieved from www.epa.gov/iaq/moisture

U.S. EPA. (2015a). eGRID2012 Summary Tables (created 10/05/15). Retrieved December 10, 2015, from http://www2.epa.gov/sites/production/files/2015-10/documents/egrid2012_summarytables_0.pdf

U.S. EPA. (2015b). Proposed Rules to Implement the Formaldehyde Standards for Composite Wood Products Act. Retrieved July 22, 2016, from https://www.epa.gov/formaldehyde/formaldehyde-emission-standards-composite-wood-products#proposedrule

U.S. EPA. (2015c). The Social Cost of Carbon. Retrieved from http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html

U.S. EPA. Formaldehyde Emission Standards for Composite Wood Products, Pub. L. No. EPA-HQ-OPPT-2016-0461, Effective Date Feb 10, 2017 (2016). U.S.A.: Federal Register of December 12, 2016 [81 FR 89674] [FPL-9949-90]. Retrieved from https://www.regulations.gov/document?D=EPA-HQ-OPPT-2016-0461-0001

U.S. EPA(DRAFT). (2010). DRAFT - TOXICOLOGICAL REVIEW OF FORMALDEHYDE - Inhalation Assessment. Retrieved from http://cfpub.epa.gov/ncea/iris_drafts/recordisplay.cfm?deid=223614

U.S. GSA. (2013). *Living in a High-Performance Green Building: The Story of EPA's Region 8 Headquarters*. Retrieved from http://www.gsa.gov/portal/mediaId/179059/fileName/High_Performance_Green_Building_-_Full_Report

U.S. National Library of Medicine. (2016a). Toxnet - Acetaldehyde. Retrieved from https://toxnet.nlm.nih.gov/cgi-bin/sis/search2/f?./temp/~wMruYq:1

U.S. National Library of Medicine. (2016b). Toxnet - Acetic Acid. Retrieved from https://toxnet.nlm.nih.gov/cgi-bin/sis/search2/f?./temp/~H1UNY2:1

United States Government Interagency Working Group on Carbon. (2015). *Technical Support Document: - Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Retrieved from file:///G:/Valuation of IAQ & Energy/Social-Cost-of-Carbon-for-RIA.pdf

US Inflation Calculator. (2017). Consumer Price Index Data fro 1913 to 2017 US Inflation Calculator. Retrieved March 3, 2017, from http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/

van Gestel, C. A. M., Jonker, M. J., Kammenga, J. E., Laskowski, J. E., & Svendsen, C. (2011). *Mixture Toxicity*. Boca Raton: CRC Press.

Walker, I. S. (2006). *Residential Furnace Blower Performance, LBNL 61467*. Berkeley, CA.

Walker, I. S. (2007). *Comparing Residential Furnace Blower for Rating and Installed Performance, LBNL 62344*. Berkeley, CA.

Walker, I., & Wilson, D. (1998). Field Validation of Algebraic Equations for Stack and Wind driven Air Infiltration Calculations. *International Journal of HVAC&R Research (Now ASHRAE HVAC&R Research Journal)*, *4*(2).

Wang, H. C., Kang, S. Y., Tseng, C. H., Shau, W. C., & Chen, Z. Y. (2011). A Novel Approach of Chitosan Additive to Remove Formaldehyde from Building Materials. *Advanced Materials Research*, *335–336*, 1174–1180. http://doi.org/10.4028/www.scientific.net/AMR.335-336.1174

Wang, J. (2014). *Assessing Sheep's Wool as a Filtration Material for the Removal of Formaldehyde in the Indoor Environment*.

WHO. (2010a). *Characterizaton and Application of Physiologically based Pharmacokinetic Models in Risk Assessment*. Retrieved from http://www.who.int/ipcs/methods/harmonization/areas/pbpk_models.pdf?ua=1

WHO. (2010b). WHO guidelines for indoor air quality: selected pollutants. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf

Wilcox, S., & Marion, W. (2008). User's Manual for TMY3 Data Sets, NREL/TP-581-43156. Retrieved from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Wolfson, M. (2013). *Defining Healthy Housing: The Competing Priorities of Energy and Indoor Air Quality in the Early 1980s* (No. W13-4). Cambridge, MA: Joint Center for Housing Studies, Harvard University. Retrieved from http://www.jchs.harvard.edu/research/publications/defining-healthy-housing-competing-priorities-energy-and-indoor-air-quality

Wolfson, M. L. (2012). *The Ecology of a Healthy Home: energy, Health, and Housing in America, 1960-1985*. Ph.D. Dissertation, Harvard University.

Wolkoff, P., & Nielsen, G. D. (2010). Non-cancer effects of formaldehyde and relevance for setting an indoor air guideline. *Environment International*, *36*, 788–799.

Xiao, G., Zhang, Z., Weber, J., Ding, H., McIntosh, H., Desrosiers, D., … Diaz-Quijada, G. (2011). Trace Amount Formaldehyde Gas Detection for Indoor Air Qulaity Monitoring. In *IEEE Instrumentation and Measurement Technology Conference Proceedings* (p. Article 4479).

Ye, W., Won, D., & Zhang, X. (2014). A preliminary ventilation rate determination methods study for residential buildings and offices based on VOC emission database. *Building and Environment*, *79*, 168–180.

Zaatari, M., Novoselac, A., Siegel, J. (2016). Impact of ventilation and filtration strategies on energy consumption and exposures in retail stores. *Building and Environment*, *100*, 186–196.

Zhang, Y., Mo, J., Li, Y., Sundell, J., Wargocki, P., Zhang, J., … Sun, Y. (2011). Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. *Atmoshperic Enviornment*, *45*(26), 4329–4343.